DESIGN AND CONSTRUCTION OF A VACUUM FURNACE

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DESIGN AND CONSTRUCTION

OF A VACUUM FURNACE

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DESIGN AND CONSTRUCTION OF A VACUUM FURNACE

SUMMARY

A vacuum furnace was designed and constructed which was capable of maintaining a pressure of 10^{-5} mm of mercury, and which would be capable of evaporating and condensing silver at the rate of 0.1 gm per minute on a surface whose temperature would be controlled and measured within plus or minus one degree Centigrade.

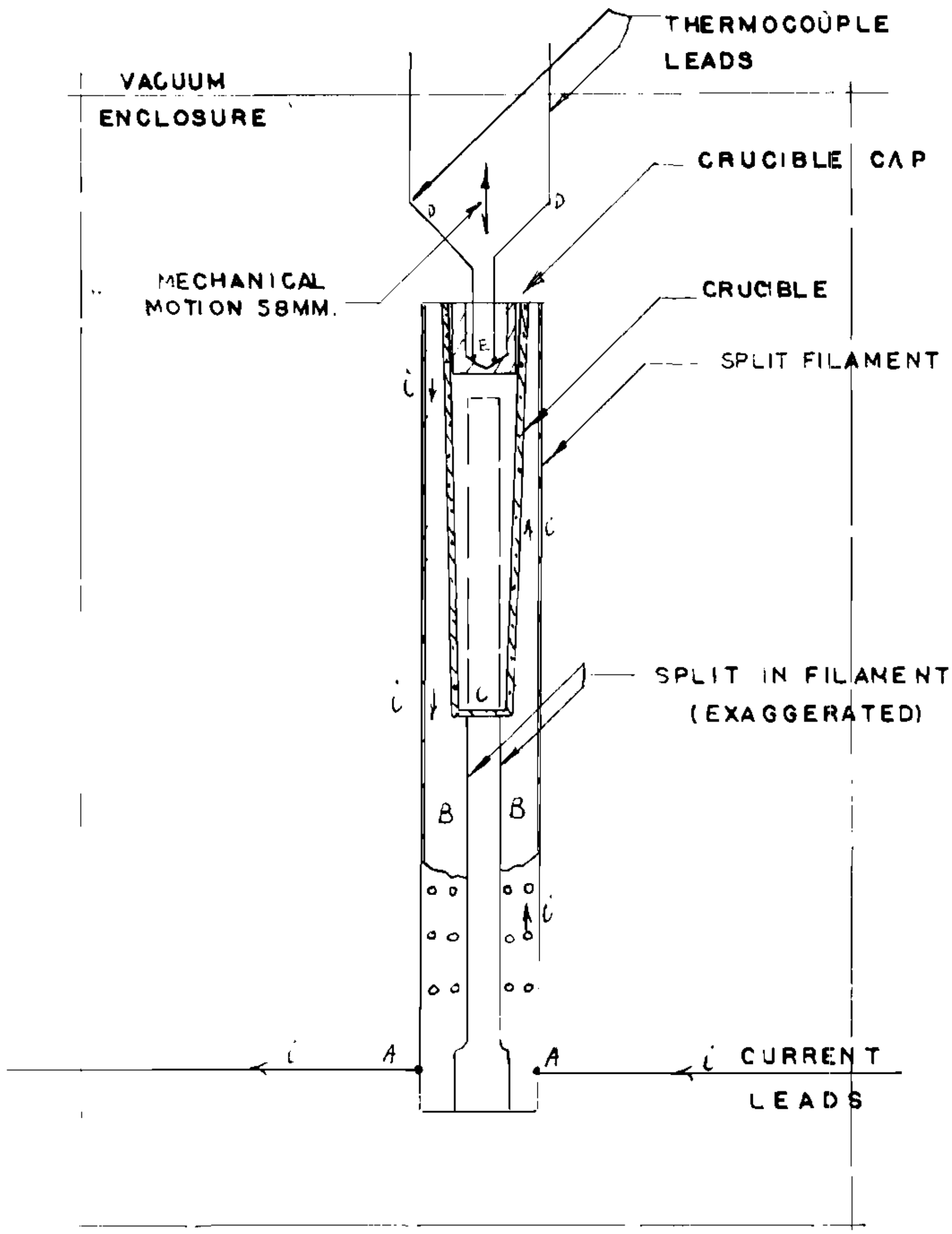
The pumping speeds of the two pumps were measured using the constant volume method. Several different pressure gauges were examined and calibrated.

INTRODUCTION

The objective of this work was to design and construct a vacuum furnace to maintain a pressure of 10^{-4} mm of mercury to evaporate silver at the rate of about 0.1 gm per minute and condense it on a surface for which the temperature could be controlled and measured to within one degree Centigrade. This problem required that silver be evaporated from the base of a long thin tubular crucible and be condensed on a surface, which formed a cap for the crucible, at a certain rate. The entire crucible, including cap, would be brought to evaporation temperature for de-gassing. In order to condense silver on the surface of the cap, the cap would then have to be at a temperature lower than that of the silver at the bottom of the crucible. Finally, the temperature of the cap would have to be known at all times.

The first problem was the production and maintenance of the specified vacuum. A vacuum system formerly used for mirror coating was modified and reconditioned for this use. This problem was considered solved when a pressure of 10^{-5} mm of mercury was produced in a relatively short pumping time and maintained. Pressures as low as 2×10^{-6} mm of mercury were obtained and measured. In the reconditioning process several methods of leak testing were used successfully.

The second problem was concerned with the heat production elements, i.e., the filaments and crucible. The crucible to be used, C in Figure 1, was in the shape of a frustrum of a cone. The cap fitted snugly just inside the open top of the crucible. The crucible was



SKETCH — FILAMENT AND CRUCIBLE

FIGURE 1

heated by a split tubular filament, B in Figure 1, made from molybdenum sheet. It consisted of two sections, each split up the middle to within an inch of the top. The current paths through the filament are denoted by i and an arrow in Figure 1. At a given instant the current could be flowing from the current leads to the split section of the filament, then up one side of each section, across the top, down the other side of each section and out through the other current carrying lead. These filament sections, which were designed and used successfully by J. H. Howey[1] to evaporate and condense silver, had to be supplied with a current of 100-200 amperes from outside the vacuum enclosure. Because the filament would be at a high temperature, the current carrying leads would have to be water-cooled. It was necessary that they make a satisfactory electrical contact with the filament and support it parallel to the axis of the crucible. This was the second problem to be solved.

This second problem was considered solved when the water-cooled electrodes were constructed and fitted with clamps or filament holders which clamped the filament around an insulated supporting ring. The electrodes were brought into the vacuum enclosure by means of a sliding O-ring seal from each side of the furnace, so that atmospheric pressure provided the clamping pressure on the filaments to give electrical contact and support.

In order that the entire crucible be at the same temperature during one sequence of the operation and that in another sequence the cap would be at a temperature lower than the bottom of the crucible,

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[1] J. H. Howey, "Non-Cubic Growth of Single Crystals of Silver by Condensation from Vapor," Physical Review, 55:578, (1939).

some method of raising and lowering the crucible relative to the split filament had to be devised. This mechanical motion had to be externally controlled. This was the third problem. A flexible sylphon bellows, actuated by an external screw, provided the mechanical motion to raise and lower the crucible supports. The motion provided was in excess of the length of the crucible.

The final problem was to be able to measure the temperature of the crucible cap at all times. This required that a complete thermocouple circuit be brought through the walls of the vacuum enclosure from the outside to the crucible cap without introducing an intermediate metal into the circuit. This was accomplished by using the large thermocouple rods as the crucible supports. The rods were brought through the walls of the enclosure by means of insulating O-ring seals at the top of the bellows. To each thermocouple rod was attached, by means of a set screw, another thermocouple lead which went to the crucible cap, D in Figure 1. As the bellows assembly was compressed and expanded, the crucible was lowered and raised relative to the filament, and the temperature of the cap was raised and lowered by means of the mechanical motion introduced through the thermocouple support rods. This problem was considered solved since no intermediate metal was introduced into the thermocouple circuit, and it would be possible to measure the temperature of the cap at all times, since the thermocouple leads formed a junction in the crucible cap.

VACUUM PUMPING APPARATUS

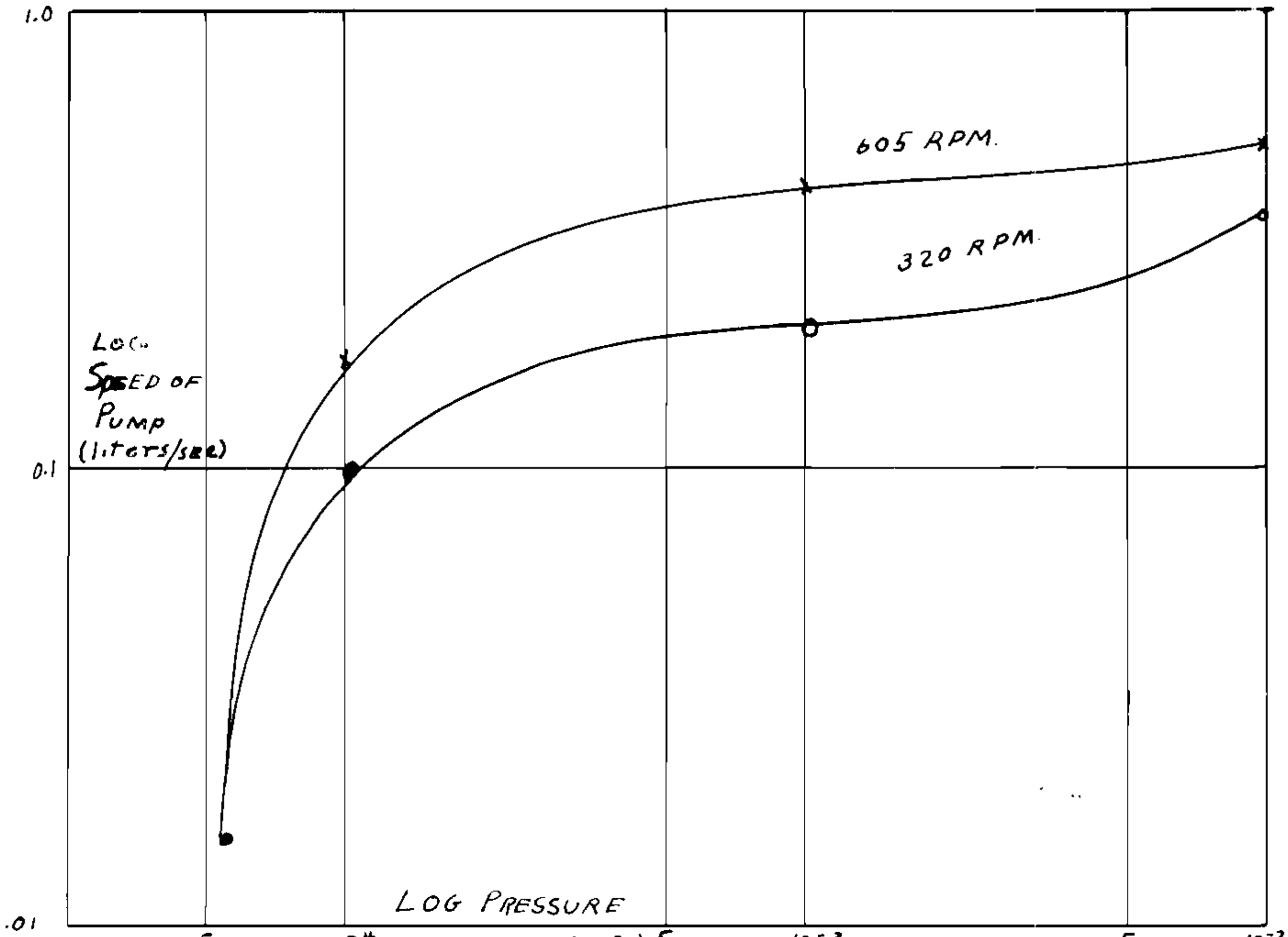
The fore pump chosen was the Central Scientific Company Megavac mechanical pump (No. 5790). It is driven by a 1/2-hp electric motor at a speed of 720 rpm. Figure 2 shows a plot of log speed of the pump in liters per second versus log pressure for this type of pump driven at 605 and 320 rpm. These data were obtained from the manufacturers. The speed of exhaust of the pump at 720 rpm was checked with the constant volume method[2] over a limited pressure range. The results are plotted in Figure 3. These data serve as an extension of the manufacturer's data inasmuch as the two figures do not overlap in pressure ranges covered. The pumping speed in Figure 3 is lower than the manufacturer's data in Figure 2 as no correction was applied for the conductance of the system and possible leaks.

The high vacuum side of the fore pump is connected to a packless, sylphon cased vacuum valve (Robertshaw Fulton Control Company, Knoxville, Tennessee) by an 18-inch piece of red rubber vacuum tubing. The inside diameter of the tubing is 5/8 inch. The valve provided a positive method of closing off the low vacuum side of the system for rate of rise of pressure measurements in leak testing.

Dow Corning High Vacuum grease was used at each rubber-to-glass and rubber-to-metal joint in the system. As little as possible of the grease was used and it was found to be satisfactory.

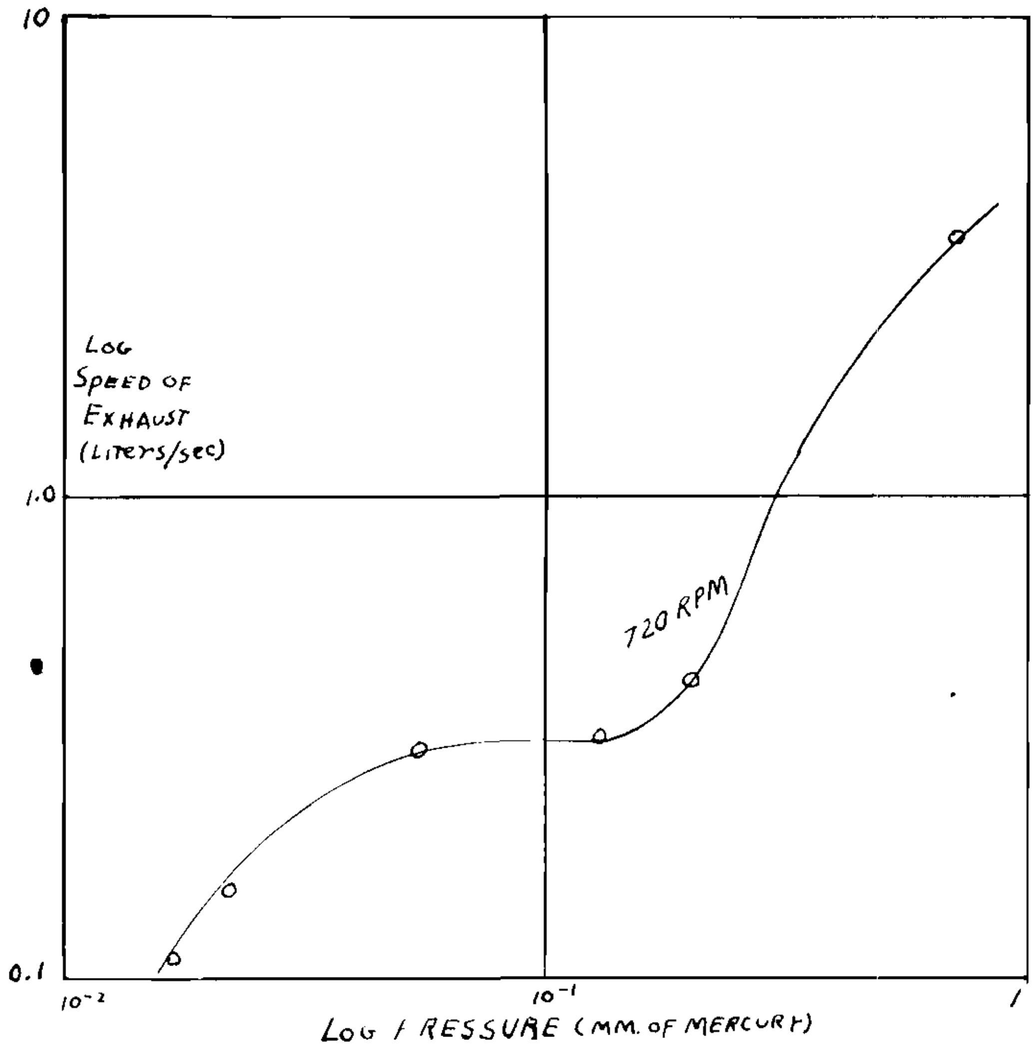
The sylphon valve was connected onto the low vacuum side of the diffusion pump with a long pipe nipple to which a cast-iron vacuum

[2]The constant volume method will be discussed more fully in the section on pressure and speed measurements.



SPEED VERSUS PRESSURE (LOG-LOG)
FOR CENCO MEGAVAC (MANUFACTURER'S DATA)

FIGURE 2



LOG SPEED OF EXHAUST VERSUS
LOG PRESSURE
FOR CENCO MEGAVC PUMP (720 RPM)
(MEASURED)

FIGURE 3

flange was silver soldered. The nipple was fitted with a brass tube threaded to admit a metal thermocouple tube to the fore side of the diffusion pump. See Figure 4.

The flat vacuum flange was connected, with a neoprene gasket, to a similar flange on the low vacuum side of the vapor pump. The flanges were clamped together with small U clamps of the type shown in Figure 5.

The neoprene gasket was cut with the outside diameter larger than the flange to enhance leak detection at this spot. The hole in the center of the gasket was slightly larger than the inside diameter of the pipe.

The diffusion pump was a Distillation Products, MC-275, oil vapor pump. The following dimensions of the pump are from the manufacturer's data sheet.

Physical Data

High Vacuum Flange	3-7/8" ID 6" OD
Fore Pump Flange	1-5/8" ID 3-3/4" OD
Height	20"
Length	12"
Width	6"

Construction

Casing	Seamless steel
Jet Assembly	Aluminum
Cooling	Water
Weight	11-1/2 pounds net

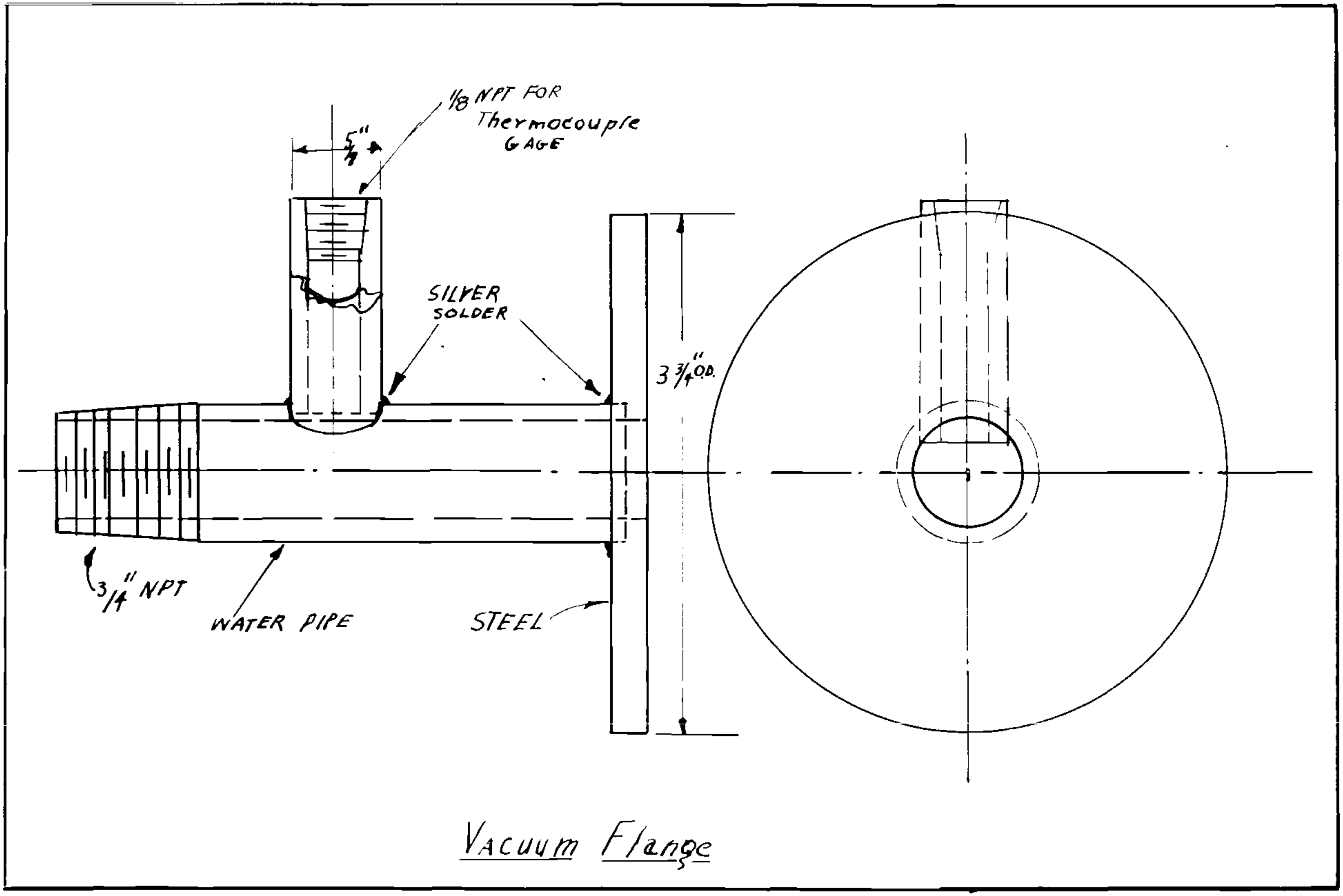

1/8 NPT FOR
Thermocouple
GAGE
5"/4
SILVER
SOLDER
3 3/4" O.D.
3/4" NPT
WATER PIPE
STEEL
Vacuum Flange

FIGURE 4

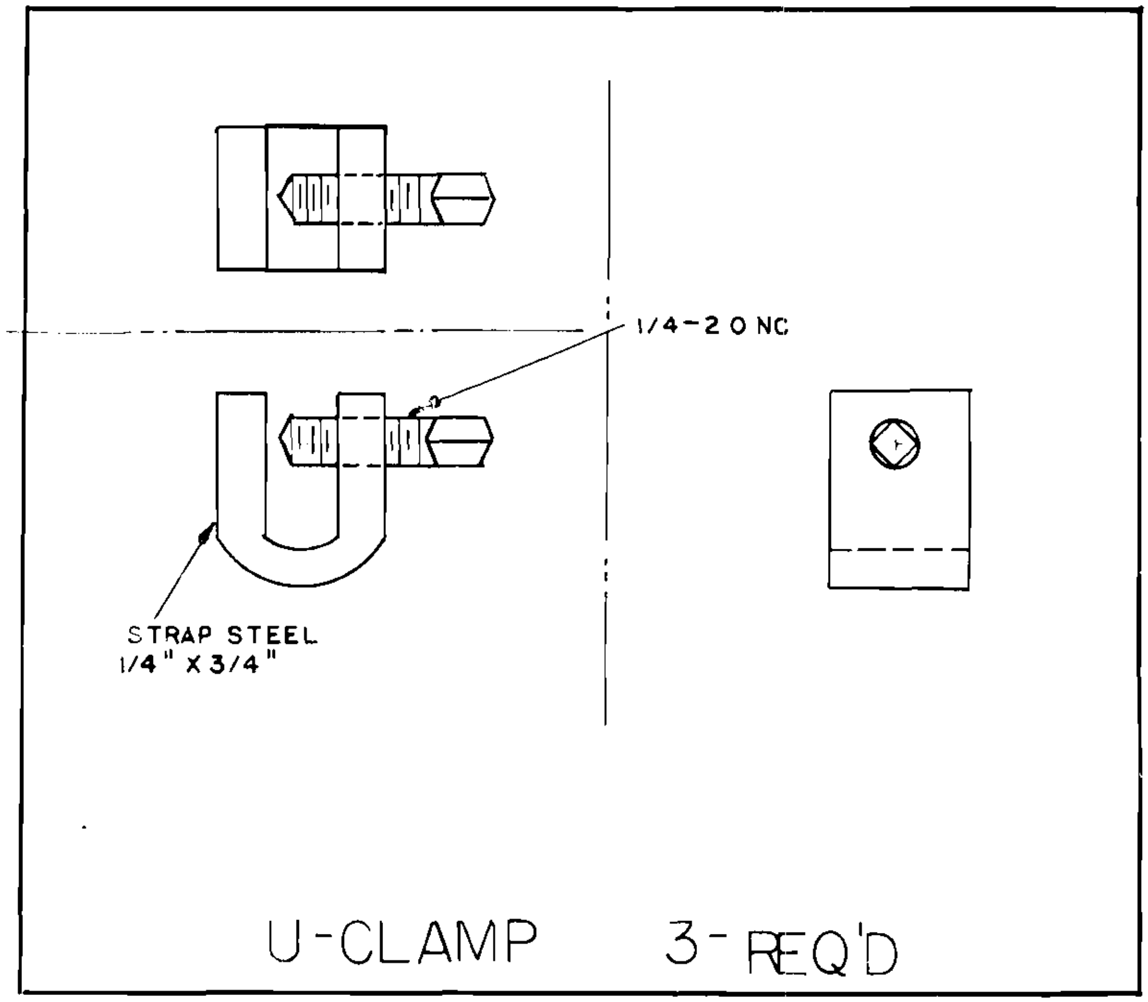


FIGURE 5

Operation Data

Amount of Oil	200 gm
Recommended Oils	Octoils; Amoils
Fore Pressure	0.10 mm
Heater Power	250-450 watts
Heater Current	2.75-3.75 amperes
Heater Voltage	90-120 volts ac or dc
Speed	275 liter/sec at 10^{-4} mm
Ultimate Vacuum	5 x 10^{-6} mm at 25°C.

"The type MC-275 unit is made semi-fractionating by the vapor-fluid interaction along the pump wall, which becomes progressively warmer as the oil flows downward, and by the water-cooled trap on the side arm. Pressures as low as 3 x 10^{-6} mm may be obtained without the use of cold traps."[3] The manufacturers further recommend that a water baffle of their own design be used to prevent the direct flight of scattered oil molecules into the apparatus.

A water-cooled baffle was used. It consisted of a 4-1/2" OD brass pipe, wrapped with 1/4" copper tubing in a helix. The tubing was soft-soldered to the outside of the pipe. Inside the pipe were two or three semi-circular baffles of copper, spaced about one inch apart and soft-soldered in place. The copper tubing was connected to the water cooling system.

The lower cooling coil of the diffusion pump was not used, but the other two coils were connected in series with the baffle coil and

[3]From the manufacturer's catalog.

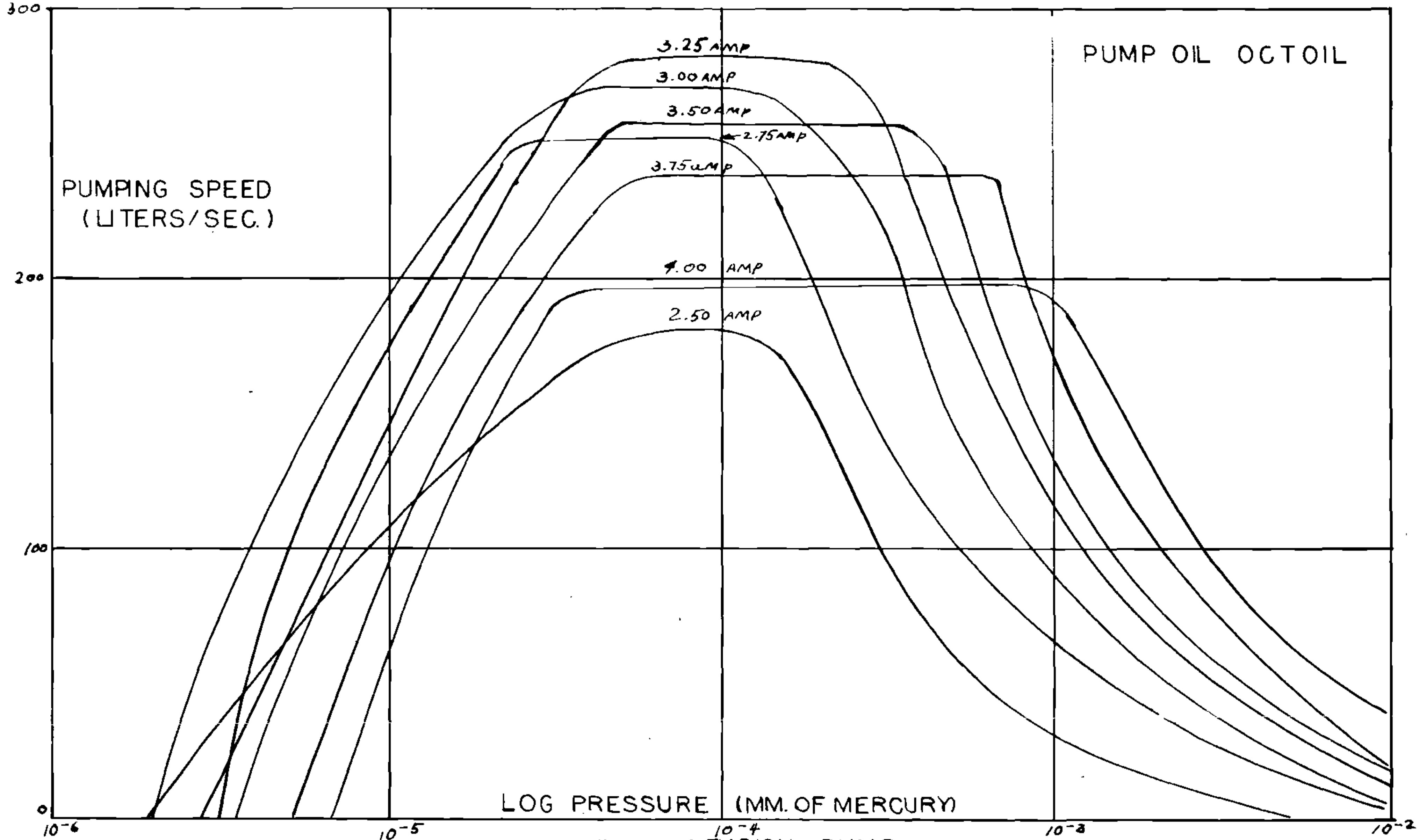
the tap water supply.

The oil used in the pump was Dow Corning DC 703 Silicone fluid (Dow Corning Corporation, Midland, Michigan). The choice of this oil was an arbitrary one; the pump contained some of the DC 703 when first pressed into service.

Numerous tests were made with the vacuum pumping system to determine the pumping speeds of the diffusion pump at various heater input powers. Typical curves supplied by the manufacturer are given in Figure 6. This curve represents the rated pumping speed of the MC-275 diffusion pump using Octoil fluid. In Figure 7 the results of measurements of the "speed of exhaust" of the pump over a limited pressure range using DC 703 fluid are given. The speeds shown in this graph were considerably lower than those of the manufacturer, because the results in Figure 7 reflect the rate at which the pump was able to exhaust the system without any corrections for conductance of the various tubes, apertures and baffles of the system. If corrections for conductance were applied to the results of Figure 7, it was felt that the manufacturer's data would have been confirmed.

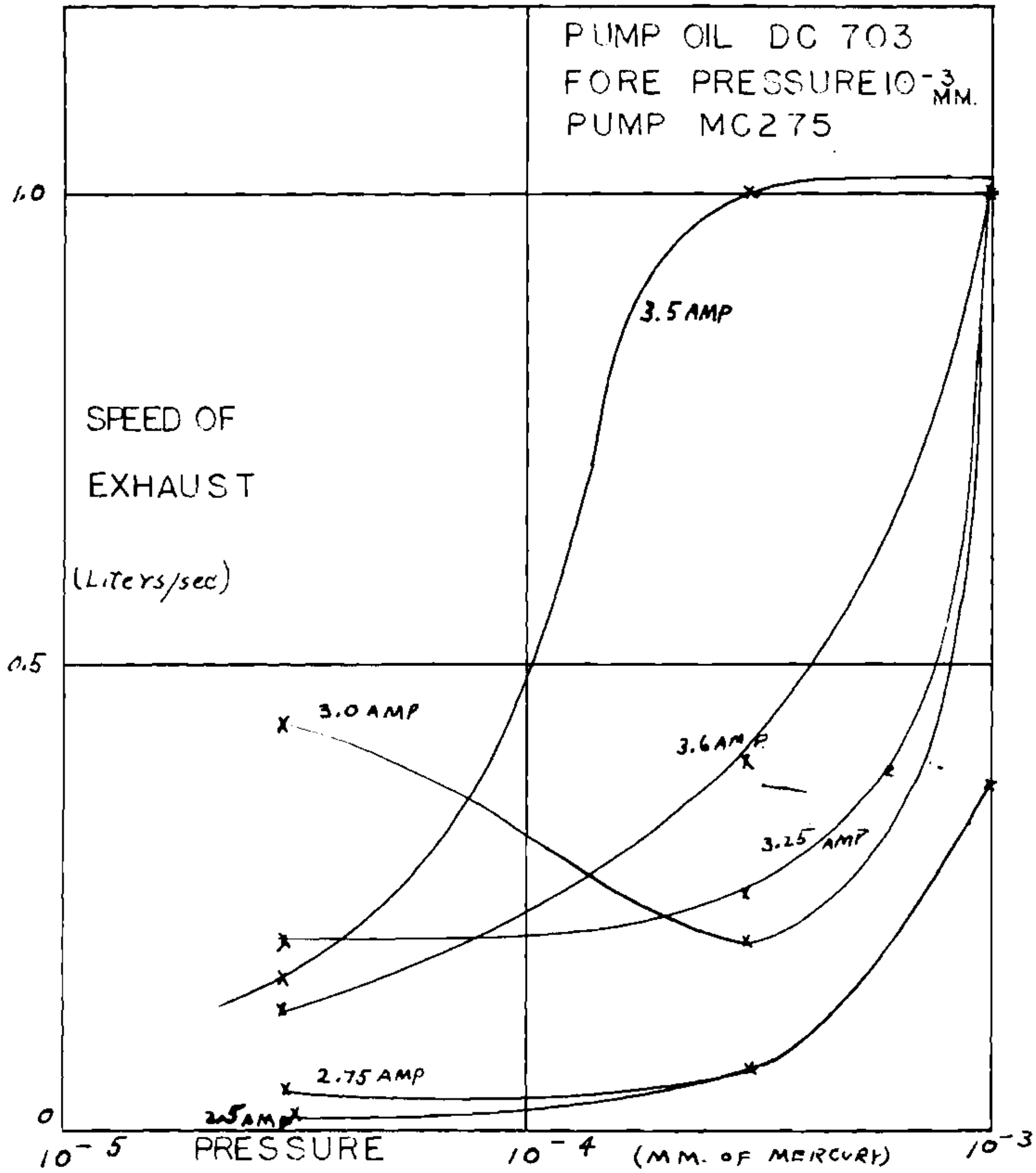
The speed of any diffusion pump is a function of the fore pressure applied to the pump above a critical fore pressure, provided the high vacuum pressure is kept constant. Figure 8 shows this fact very clearly. These data, again, were supplied by the manufacturer of the diffusion pump. No attempt was made to duplicate these measurements.

The voltage applied to the heater coil was controlled by a variac. To prevent operation of the diffusion pump during a period in which the coolant failed or water pressure diminished, a relay, controlled by a



D.P.I. METAL DIFFUSION PUMP
TYPE MC 275
(MANUFACTURER'S DATA)

FIGURE 6

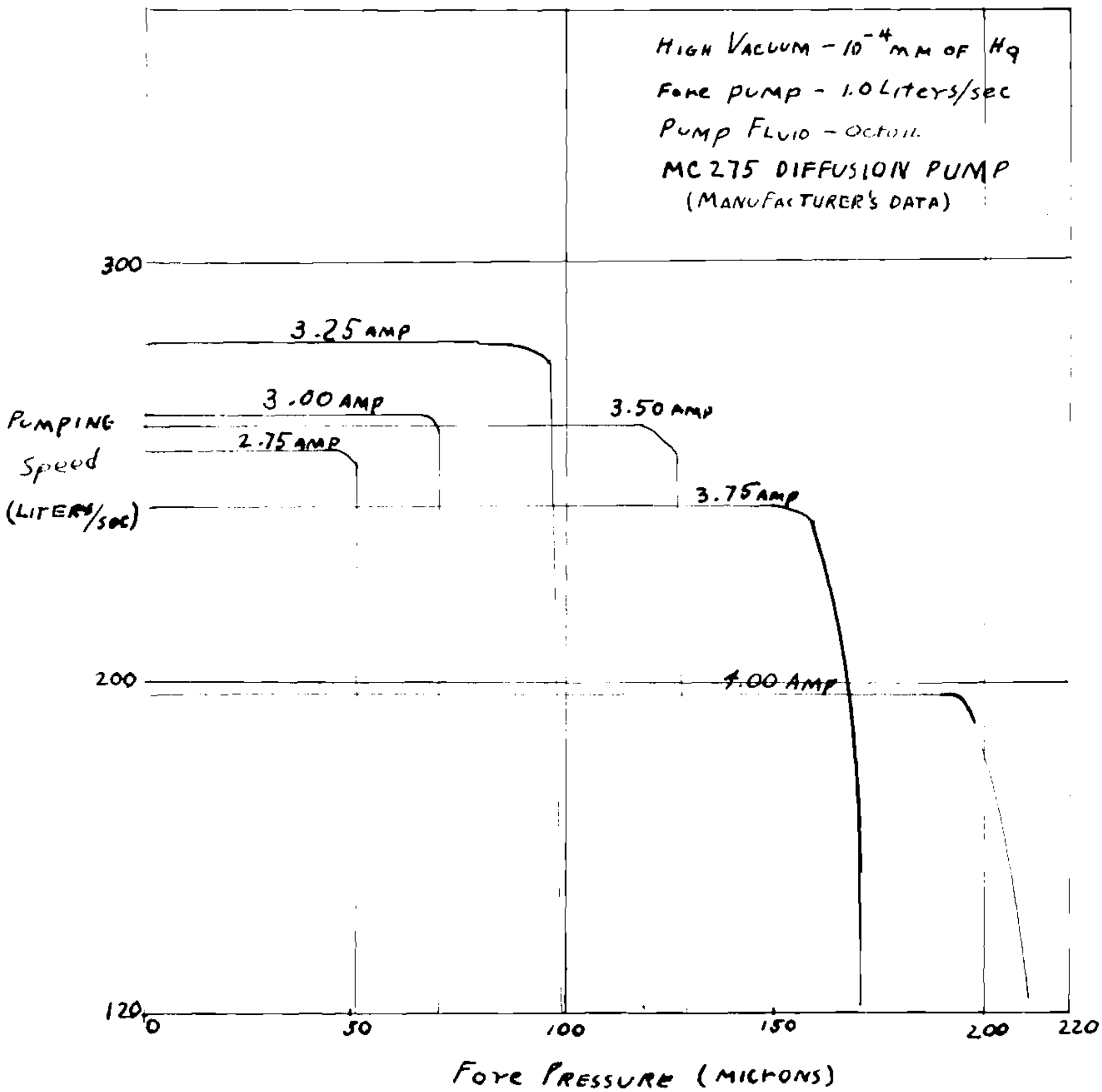


SPEED OF EXHAUST (MEASURED)

VS

PRESSURE

FIGURE 7



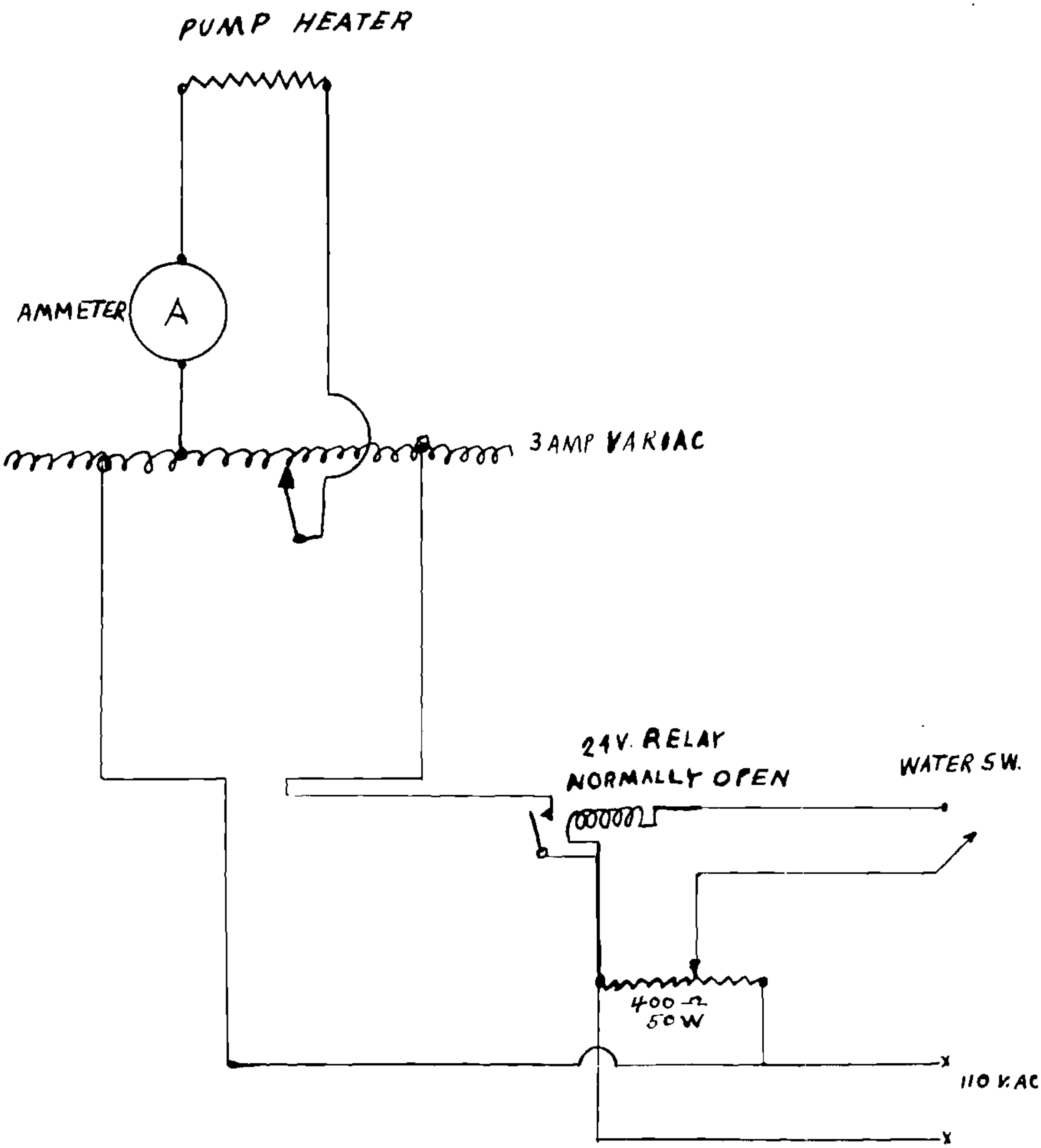
Pumping Speed vs. Fore Pressure

FIGURE 8

water actuated switch, was placed in series with the heater circuit. The heater control circuit is given in Figure 9.

The entire pump, including baffle, was mounted below a standard laboratory table. The base of the diffusion pump was fastened with iron straps to a small table on the floor. The cooling baffle tube extends through a hole in the table to an aluminum platform which was mounted several inches above the table top. A four-inch hole was cut in the aluminum base, and the baffle tube was fastened to the base with a neoprene gasket seal and six bolts. The aluminum base provided a smooth, well-finished base upon which to mount the furnace.

Figure 10 is a photograph of the entire apparatus and arrangement. The two switches on the baseboard of the table controlled the outlet boxes for the fore pump and the diffusion pump heater circuit.



DIFFUSION PUMP HEATER
CONTROL CIRCUIT

FIGURE 9

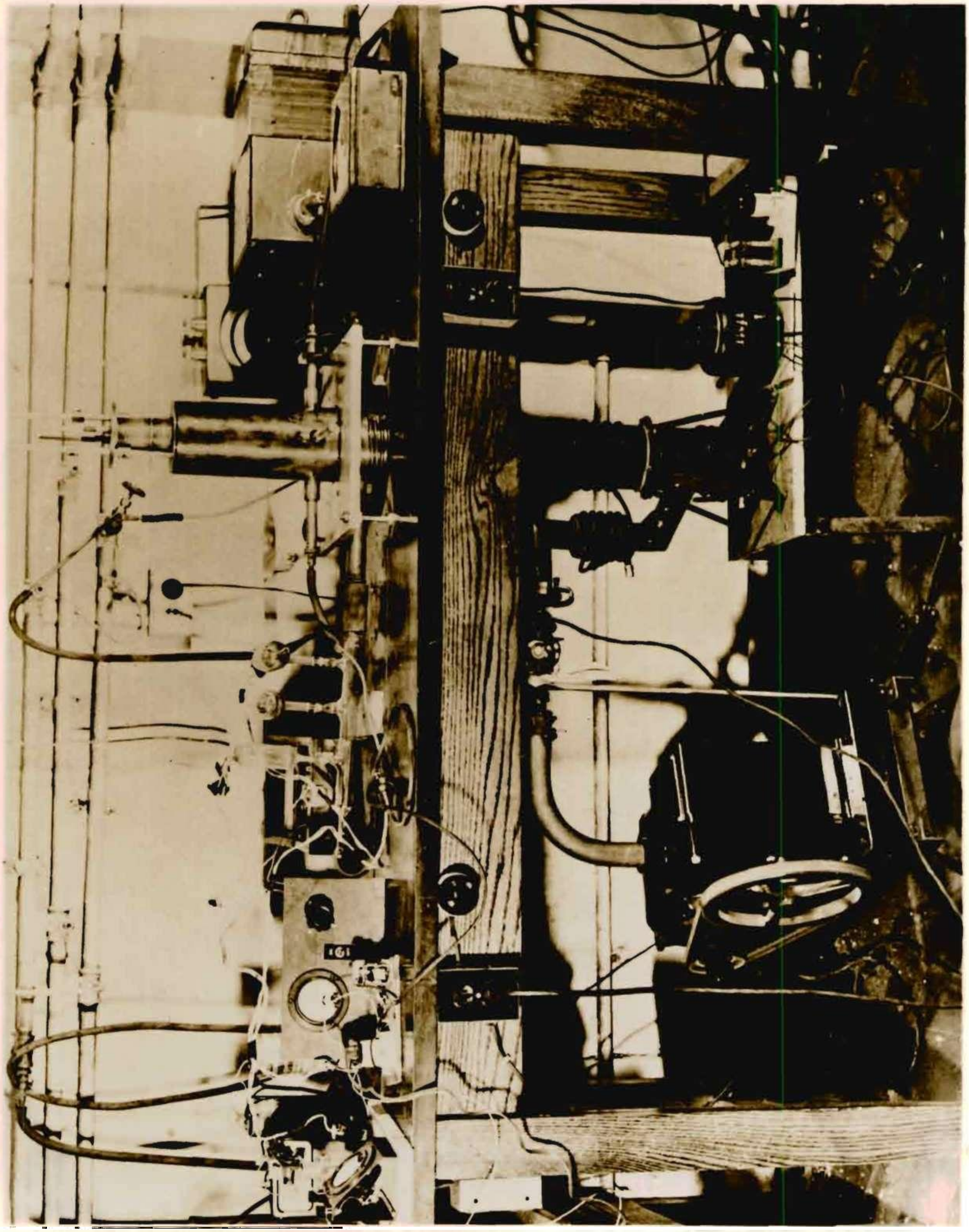


FIGURE 10

VACUUM FURNACE APPARATUS

The furnace itself needed to be rigid, vacuum tight, and easily accessible. A method of bringing water-cooled electrodes into the furnace and a method of altering the position of the crucible relative to the filament had to be provided.

Brass was chosen for the material of construction, wherever possible, because it is easily machined. All parts, except the filament support ring and holders, crucible cap, and the thermocouple rods were made of brass.

The foundation for the furnace was a large piece of red brass pipe. The pipe was provided with two side ports or sleeves for the water-cooled electrodes and a port to which was fitted the Phillips type ionization gauge. The top and bottom surfaces were machined for a groove to accommodate O-rings for the vacuum seal. In practice only the upper O-ring groove was used; a neoprene gasket served quite adequately for the bottom seal. The furnace pipe rested on the aluminum platform. Figure 11 is an exterior photograph of the furnace proper, and it illustrates the location of the side sleeves and water-cooled electrodes. The Phillips gauge is not shown in this photograph. It normally would appear in place of the brass plug which closes the port. On top of the pipe a black ring represents the O-ring seal between the sylphon bellows and the pipe proper.

Emerging from the top of the bellows can be seen the two thermocouple rods, one chromel, the other alumel. The details of the furnace pipe are given in Figure 12. It should be noted that only the horizontal

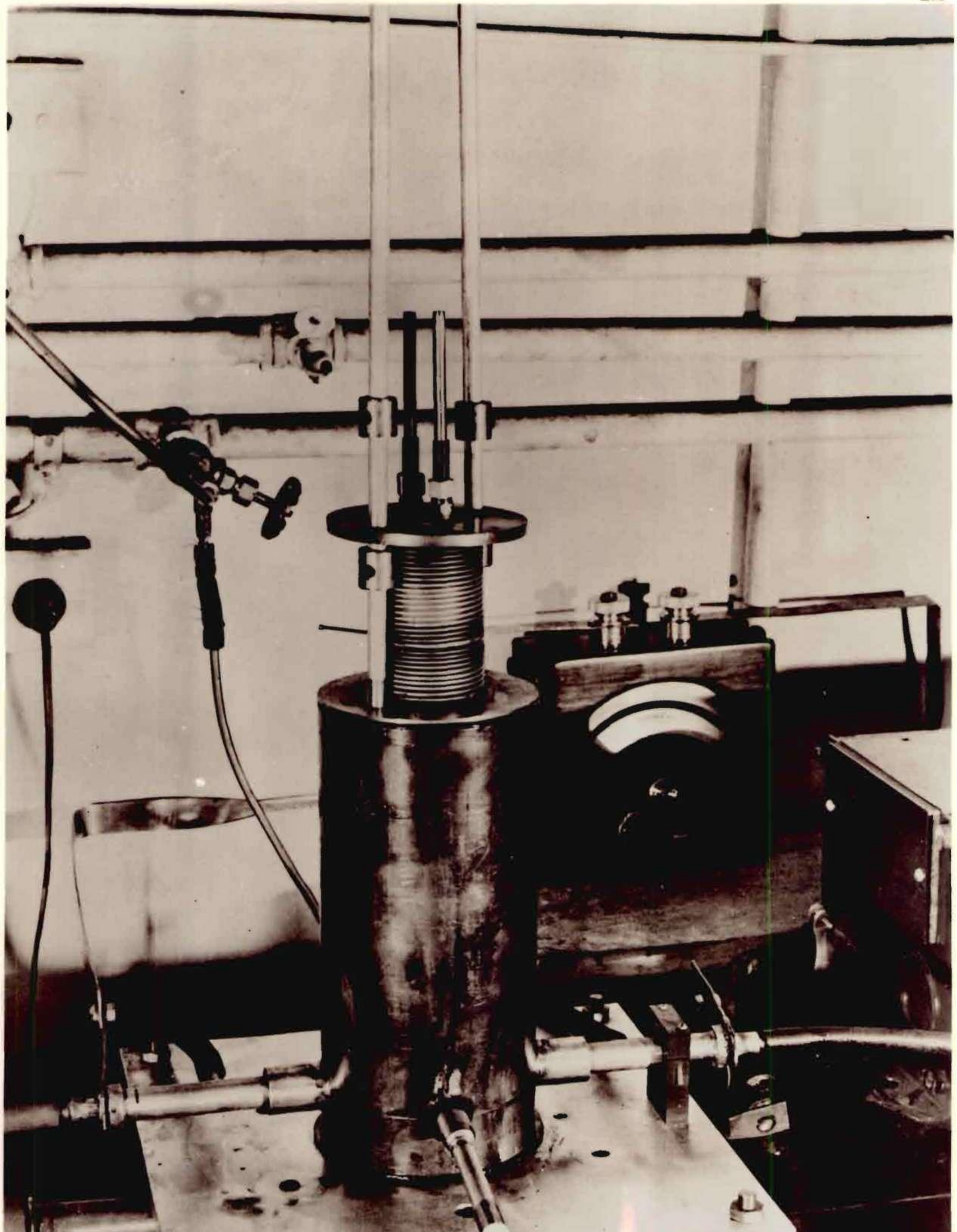
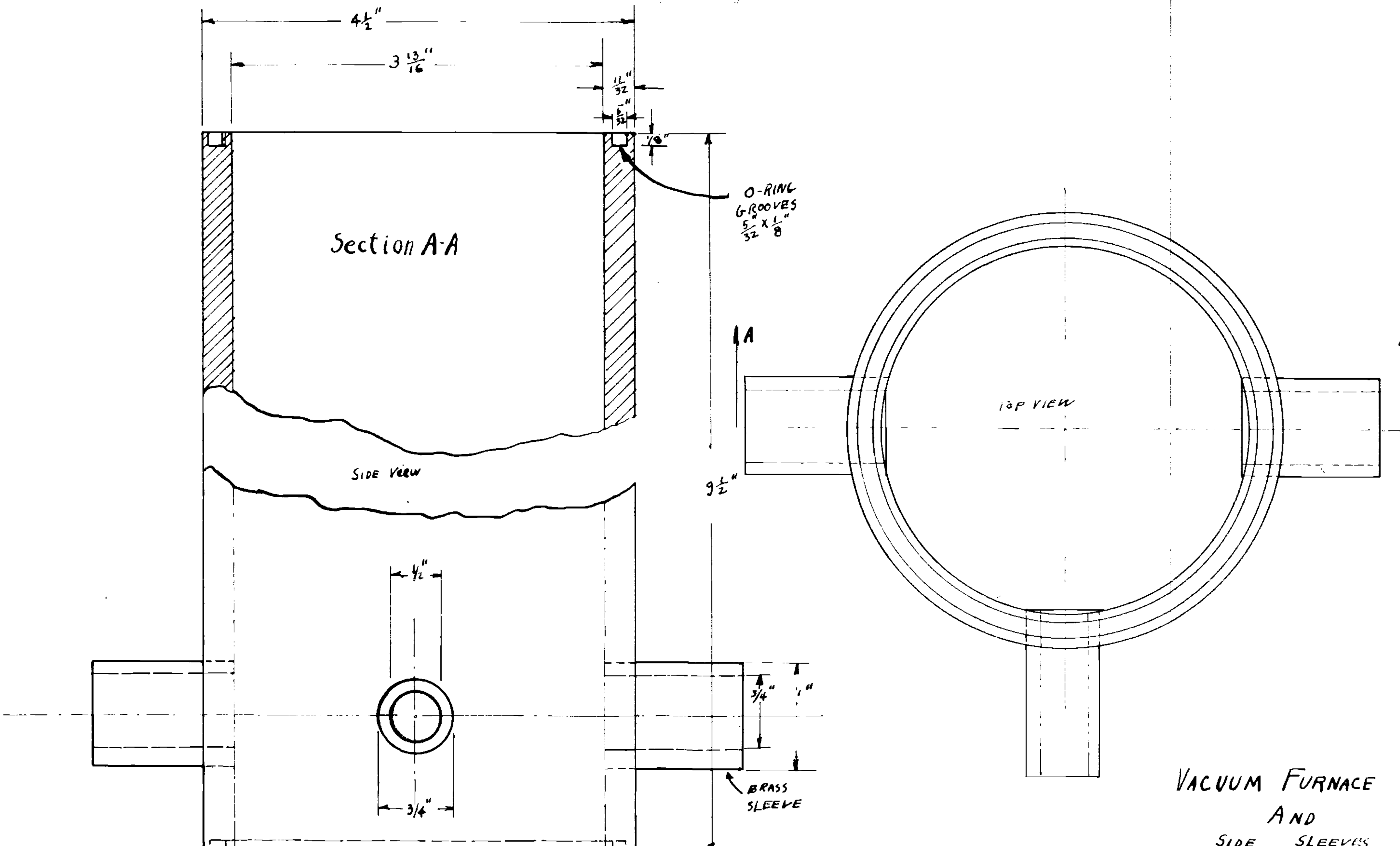


FIGURE 11



VACUUM FURNACE PIPE AND SIDE SLEEVES

FIGURE 12

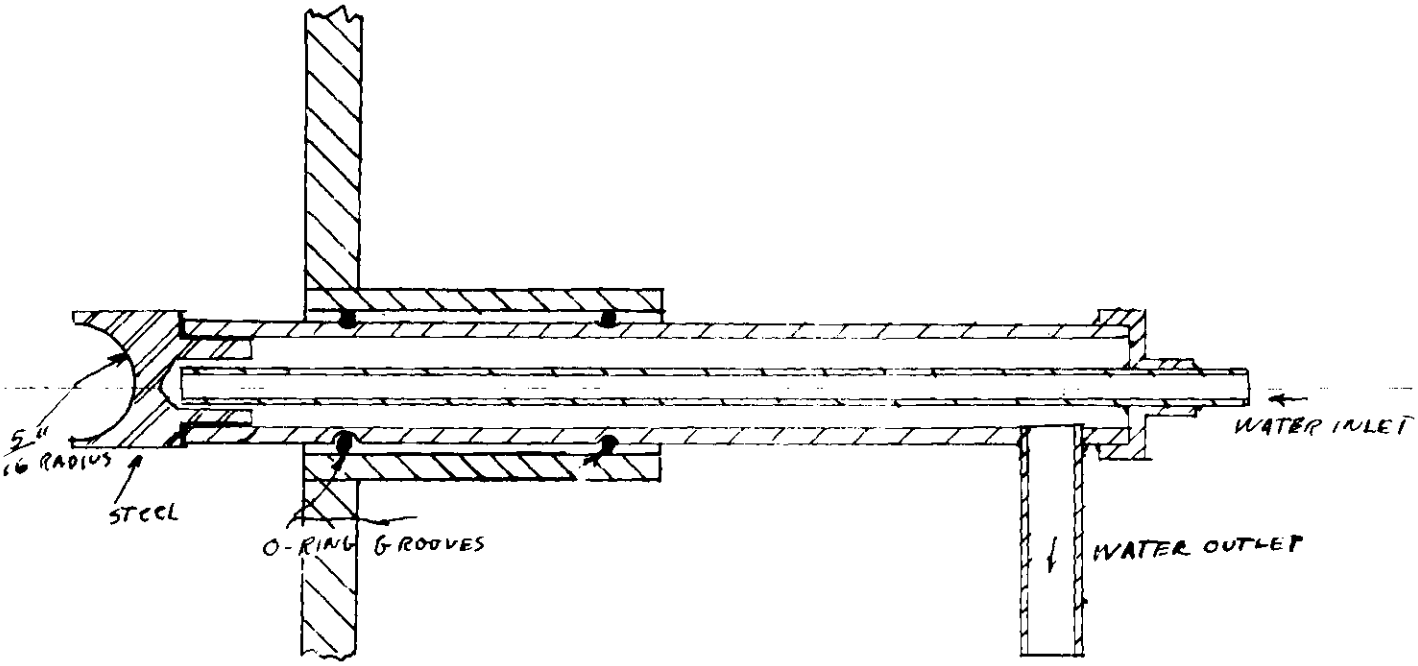
scale of this figure is drawn full size. The inside and outside surfaces of the pipe were left unfinished.

The side sleeves were of sufficient size to allow free passage of the electrodes and the filament clamps. The inside surfaces were bored and hand reamed to provide a smooth surface to seat the O-ring seal. The water jacket of the electrodes were grooved for the O-rings which were spaced about one inch apart. A cross-section drawing of the filament holders, side sleeves, water jackets, and O-ring grooves is given in Figure 13. Only the filament holders were made of steel. Most of the tubing in the water jackets was chosen from popular sizes of brass tubing to reduce the machining time.

Whenever possible, joints were silver soldered. The resulting joints were then rigid, watertight and usually vacuum-tight. The thin stock of the sylphon bellows die not permit the use of silver solder.

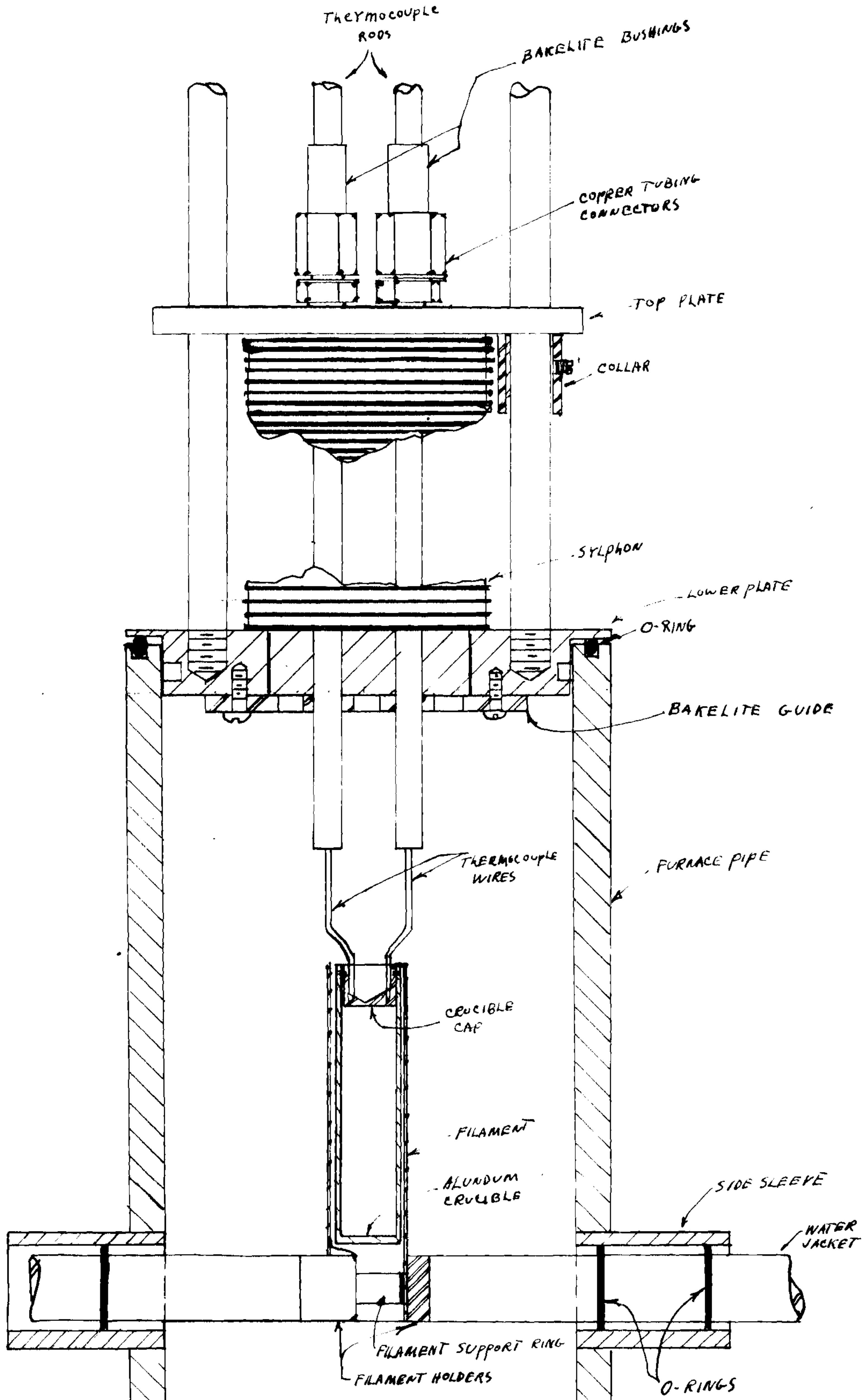
Figure 14 shows in partial cross-section the essential details of the complete furnace. The crucible and furnace head are shown in the position of lowest travel. The filament holders are clamped against the filament around the filament support ring. The details of the filament support ring are given in Figure 15. In this same figure the details of the crucible cap and the filament holders are given. The holders are of steel for strength and electrical conductivity. The support ring is insulated from the filaments with thin sheets of mica that are held in place with vacuum grease.

The crucible cap was of iron. In the drawing of the cap the threaded holes for the thermocouple leads and the holes through which the crucible was fastened in place were not shown. The holes for the



FILAMENT HOLDER
AND
WATER JACKET

FIGURE 13



GENERAL VIEW OF VACUUM FURNACE

FIGURE 14

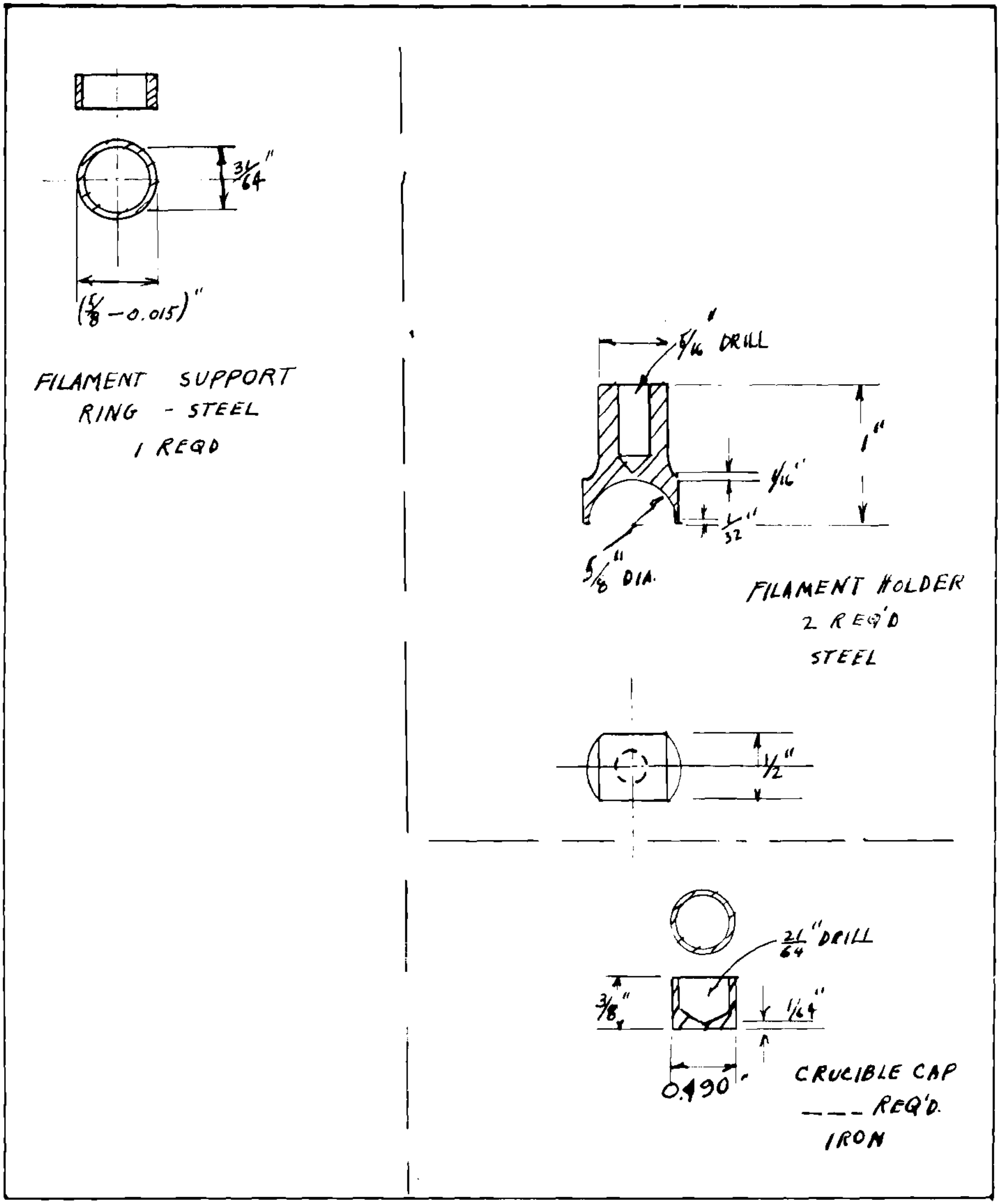
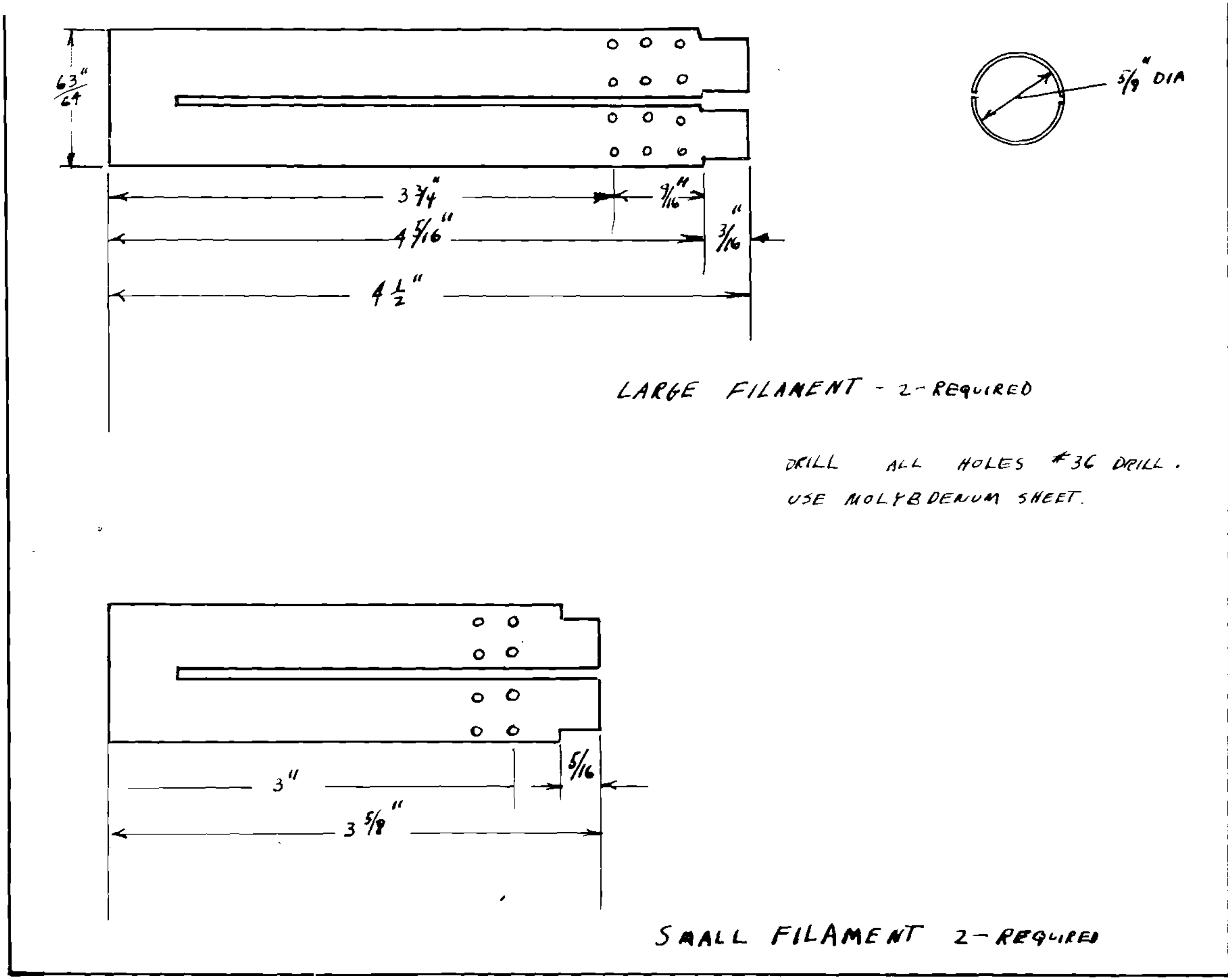

31/64"
(5/8 − 0.015)"
FILAMENT SUPPORT
RING - STEEL
1 REQD
5/16" DRILL
1"
1/16"
1/32"
5/8" DIA.
FILAMENT HOLDER
2 REQ'D
STEEL
1/2"
21/64" DRILL
3/8"
1/64"
0.490"
CRUCIBLE CAP
___ REQ'D.
IRON

FIGURE 15

thermocouple leads were tapped for an 0-80 screw. The thermocouple leads were of sufficient size to be threaded for the holes. The crucible was of alundum about 58 mm long. Two holes were drilled in the top sides of the crucible to allow a spring clip to pass through these holes and the holes in the cap. The clip was of piano wire. The cap crucible fitted closely to prevent an excess of silver from depositing elsewhere in the furnace.

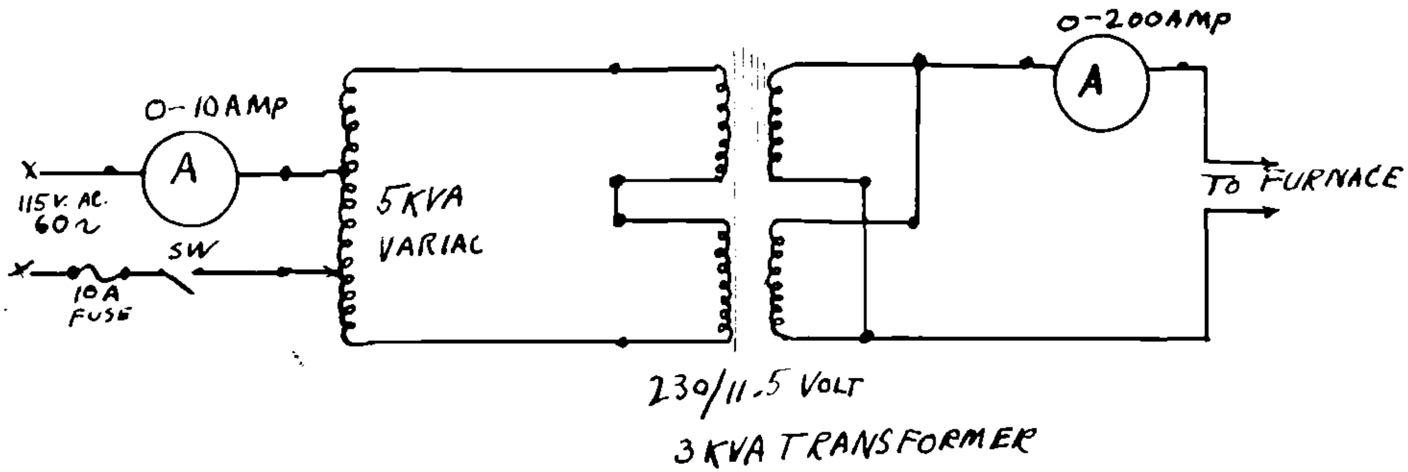
The filaments were of two sizes, one longer than the other. The details of construction are given in Figure 16. The two sections of the complete filament were formed into a 5/8" diameter tube and so placed in the clamp support ring combination that the current would flow in the two halves of each section, through each filament, and out through the other two halves into the other clamp or electrode holder. The holes were drilled in each filament section close to the base so that the temperature distribution would be fairly uniform in spite of the colder water-cooled filament holders. This arrangement was similar to that used by J. H. Howey in 1939.

The current for operating the furnace was provided through a large step-down transformer which operated from the 115-volt ac mains. (See Figure 17.) Temperature control was possible by varying the current through the filament and by varying the position of the crucible and cap relative to the filament. The current was carried from the transformer to the furnace in large copper bus-bars. The bus-bars were made of sheet copper 1/16" by 1". A current of 120 amperes, used to test the circuit, did not cause any noticeable heating of the bus-bars or terminals.



63/64"
3 3/4"
9/16"
4 5/16"
3/16"
4 1/2"
5/8" DIA
LARGE FILAMENT - 2-REQUIRED
DRILL ALL HOLES #36 DRILL.
USE MOLYBDENUM SHEET.
3"
5/16
3 5/8"
SMALL FILAMENT 2-REQUIRED

FIGURE 16



VACUUM FURNACE ELECTRICAL SUPPLY CIRCUIT

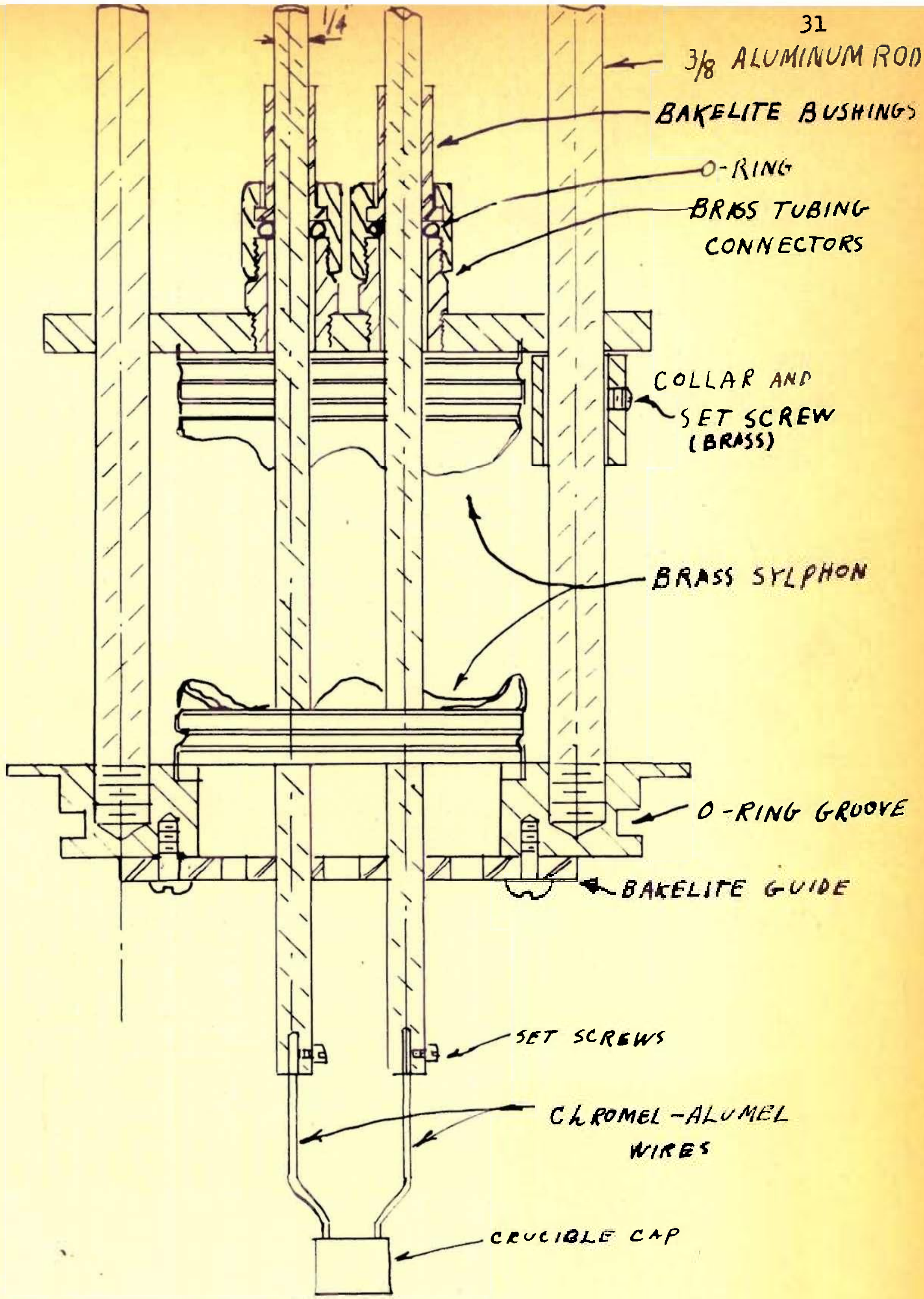
FIGURE 17

To condense the silver on the cap it was necessary for the cap to be cooler than the crucible base. This required that the crucible be withdrawn part of the way out of the filament tube. This was accomplished by the flexible sylphon bellows on the top of the furnace pipe. The thermocouple leads, which supported the crucible cap, were anchored in a plate on top of the sylphon bellows. The bellows allowed a movement of the crucible in excess of 58 mm. Guide rods of aluminum provided the necessary rigidity and alignment for the bellows. See Figure 18 for details of the entire bellows arrangement.

The bellows were supported by a brass plate which was fitted with an O-ring groove. This side groove, see Figure 19, was used for a time, but the seal was too difficult to open. The O-ring seal groove on the top of the pipe was used thereafter. A bakelite plate was attached to this brass plate to align the thermocouple rods as the bellows were expanded and compressed. The bakelite plate is described in Figure 18.

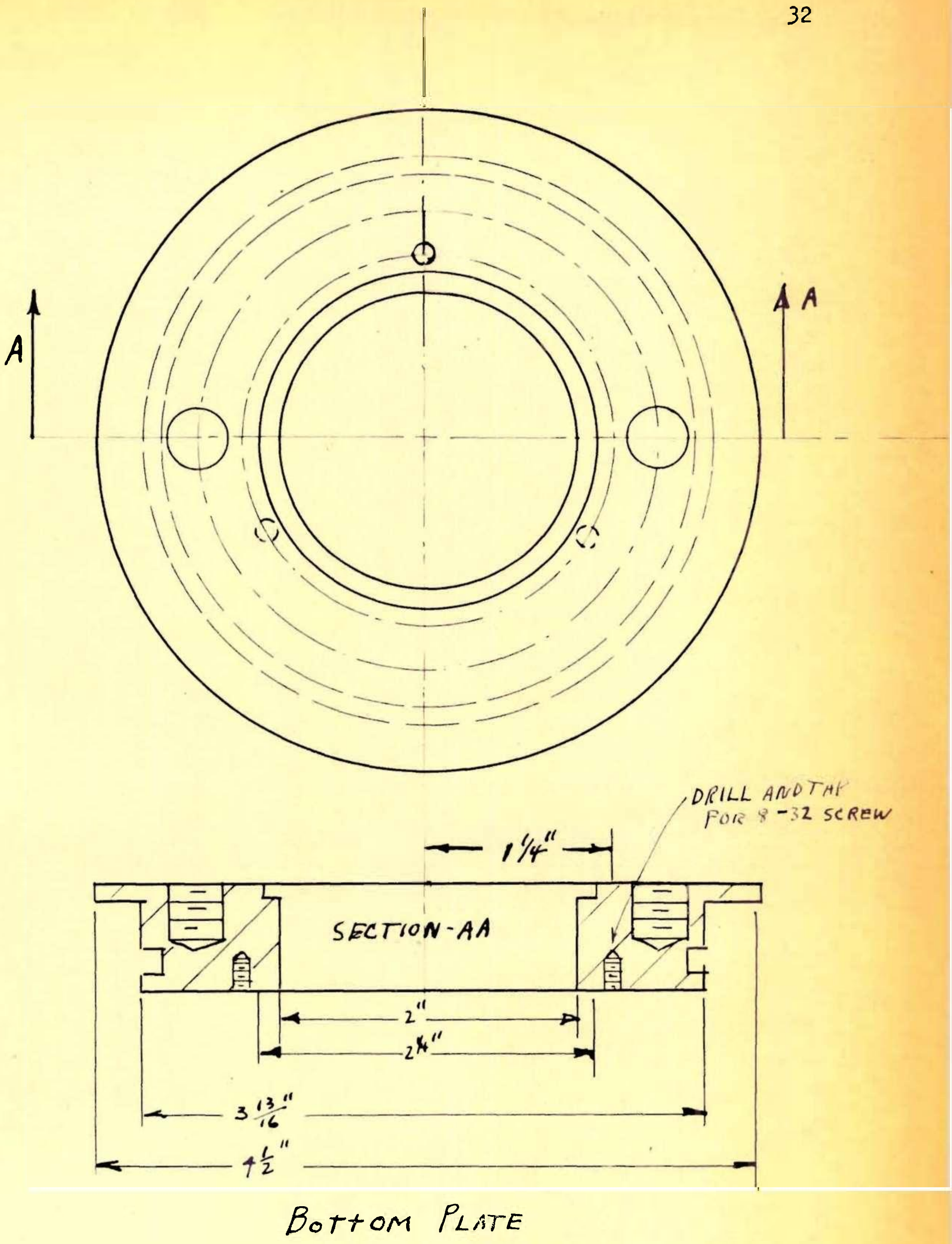
Collars with set screws were placed on the aluminum guide rods to prevent excessive movement up or down. The bellows were moved upward by means of a screw which fastened on the top of the aluminum rods. The details are given in Figure 20.

The thermocouple rods, which support the crucible, were insulated from the furnace by means of bakelite bushings and O-rings. A vacuum seal was completed when the tubing connectors compressed the O-rings. The tubing connectors were soft soldered to the top plate. These connectors allowed adjustment of the length of the thermocouple rods. Each thermocouple rod was drilled and tapped for set screws so that the thermocouple circuit was brought in through the walls of the furnace to the



Furnace Head

FIGURE 18



Bottom Plate
Brass 1-Req'd

FIGURE 19

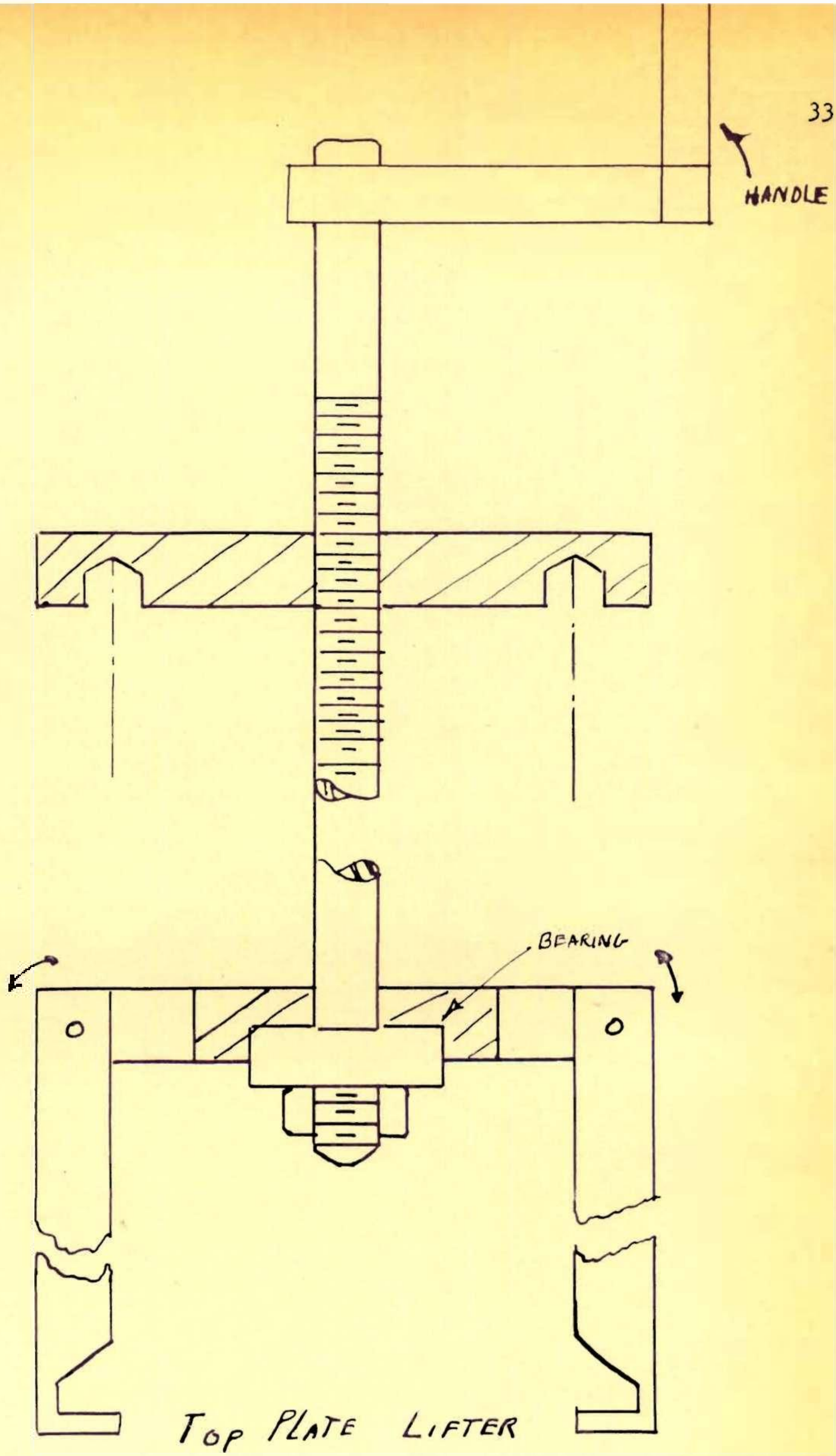


FIGURE 20

crucible cap which provided the junction.

The O-ring seals used in this furnace were suggested by a paper written by F. N. D. Kurie.[4] Data books on O-rings, while mostly for hydraulic packing, can be obtained from the two principal manufacturers.[5]

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[4] F. N. D. Kurie, "Vacuum Systems, Seals, and Valves," Review of Scientific Instruments, 19:435-43, (1948).

[5] Linear Inc., Philadelphia, Pennsylvania; Goshen Rubber and Manufacturing Company, Goshen, Indiana.

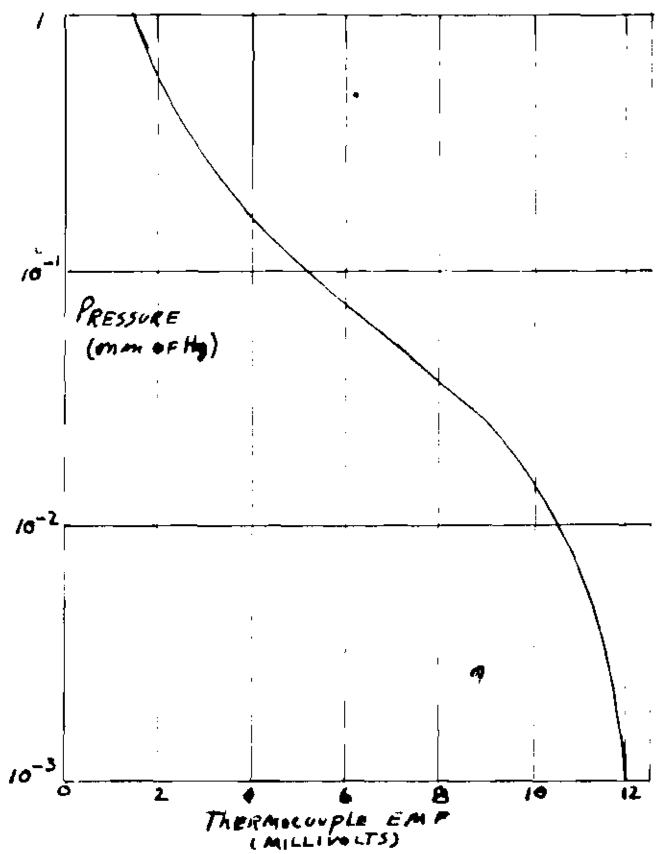
MEASUREMENT OF PUMPING SPEED AND PRESSURE

Several methods were used to measure pressure at various points in the system. Each method had its particular range of usefulness.

The first unit used was the thermocouple gauge. Two different types were used, the envelope in one case being glass, in the other case metal. The glass tube was an RCA type 1946 gauge. It was connected to the high side of the diffusion pump. It consisted of a wire, heated with a constant current, to which a thermocouple was attached. The temperature of the thermocouple junction was determined by the operating current and the heat conductivity of the residual gas. The heat conductivity of the gas was a direct function of the gas pressure. The RCA 1946 has a range from 1 mm to 10^{-4} mm of mercury. Both thermocouple gauges have the positive advantage of not being damaged in the event of a loss of vacuum.

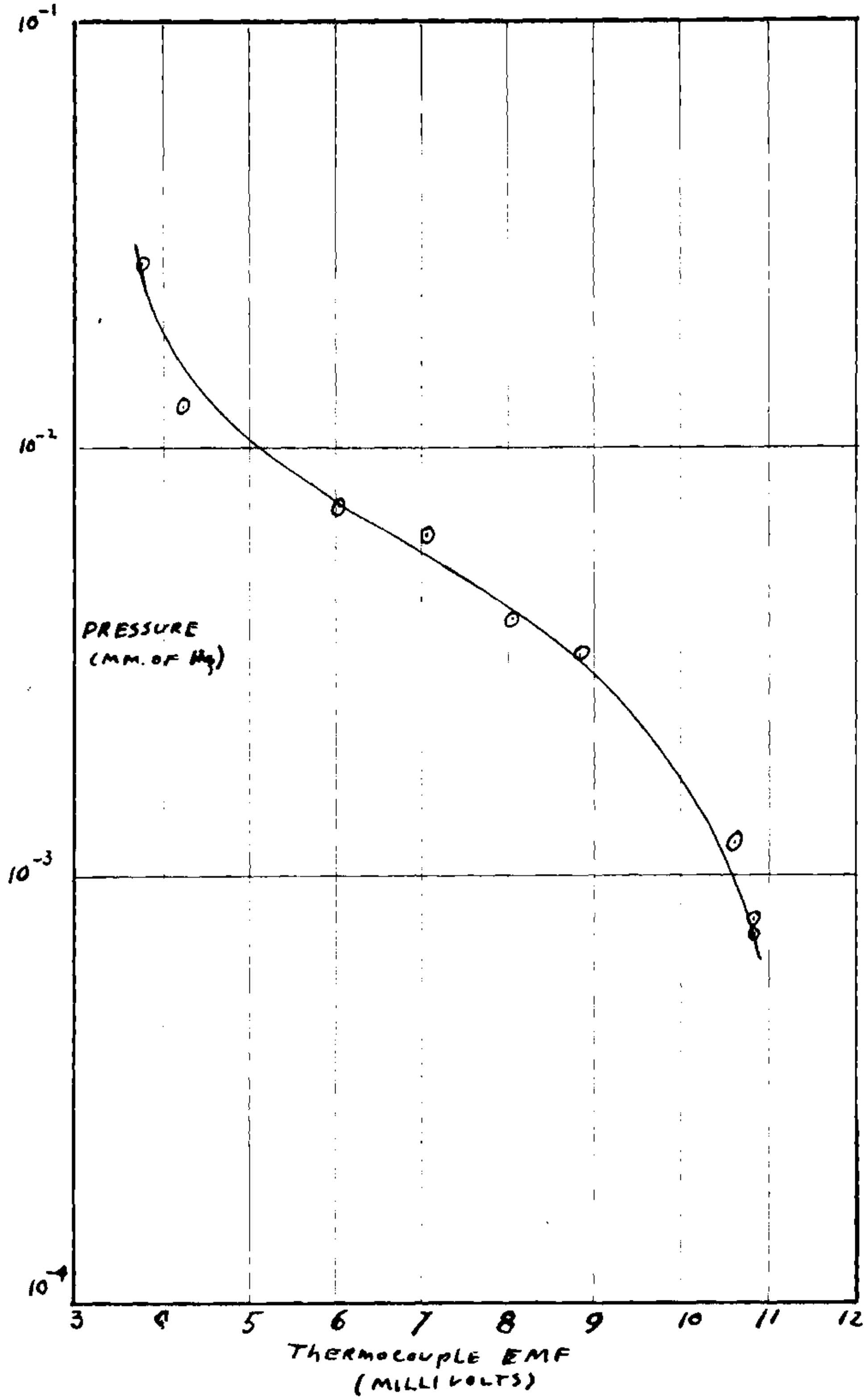
In this experiment the gauge was operated with 70 milliamperes of direct current supplied to the heater wire. The calibration curve supplied by the manufacturer is given in Figure 21. When first placed in operation, the tube was calibrated with a McLeod gauge, without a cold trap. The resulting data is plotted on Figure 22. Several months after a sudden change in readings the gauge was recalibrated. The resulting curve is given in Figure 23.

The metal thermocouple gauge was part of a Vacuum Gauge Unit Type EMG-1 (RCA). This tube was heated by current from a transformer from the 115-volt ac line. The amount of current was regulated by an adjustable resistor. This resistance was adjusted to give a maximum



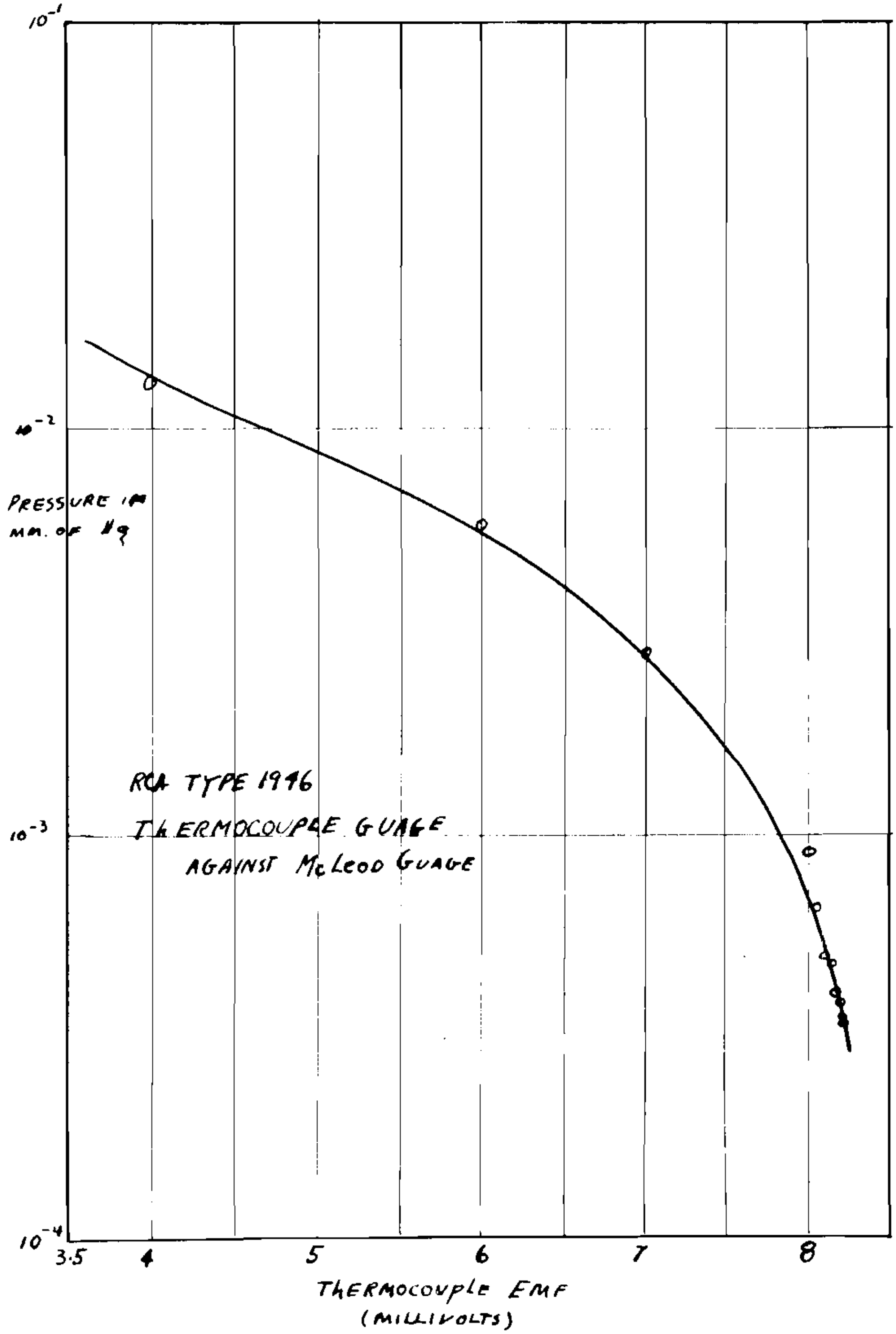
CALIBRATION CURVE (MANUFACTURER'S) FOR RCA TYPE 1946 THERMOCOUPLE GUAGE

FIGURE 21



CALIBRATION CURVE FOR RCA 1946 (AGAINST McLEOD GUAGE)

FIGURE 22



10^{-1}
10^{-2}
10^{-3}
10^{-4}
PRESSURE IN MM. OF Hg
RCA TYPE 1946
THERMOCOUPLE GUAGE
AGAINST McLEOD GUAGE
3.5
4
5
6
7
8
THERMOCOUPLE EMF
(MILLIVOLTS)

FIGURE 23

meter deflection at the lowest pressure that the gauge would recognize (10^{-4} mm of mercury). The calibration curve, Figure 24, supplied by the manufacturer, was reasonably accurate. Both of these gauges were useful for measurement of pressures from 1 mm to 10^{-3} mm of mercury and for ascertaining when the fore pressure was low enough to operate the diffusion pump.

Another unit used for pressure measurement was Penning-Phillips discharge tube which formed the other part of the Vacuum Gauge Unit Type EMG-1. In this gauge the electrons, emitted from a cold cathode of some active material, were deflected by means of a permanent magnetic field so that the total length of the path covered in reaching the anode was many hundred times the direct distance between the two electrodes. The ionization produced per electron at a given pressure was greater than would be obtained in the absence of a magnetic field. The magnitude of the total current, which includes the sum of the positive ion current and the electron current, was used as a measure of the pressure. The original gauge was made by Penning[6] of glass. It used a 2000-volt dc source. The Radiation Laboratory experimented further with this gauge and used an ac supply to the tube. It was proven that the tube was self-rectifying below a certain pressure. They found that the discharge was extinguished frequently at pressures below 2×10^{-5} mm of mercury with ac operation.[7]

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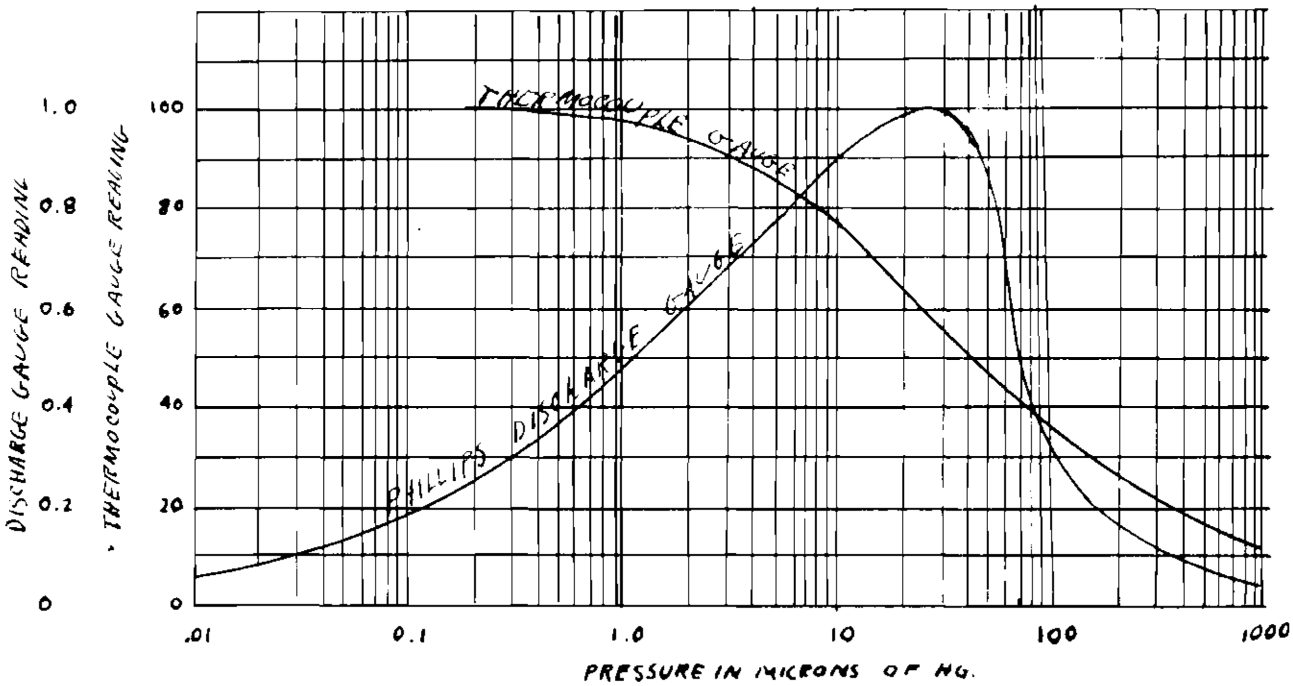
[6]F. M. Penning, "Ein neues Manometer fur niedrige Gasdrucke, insbesondere zwischen 10^{-3} und 10^{-5} mm," Physica, 4:71, (1937).

[7]A. Guthrie and R. K. Wakerling, Vacuum Equipment and Techniques, (New York: McGraw-Hill Book Company, Inc., 1949), pp. 128-39.



VACUUM GAUGE UNIT, TYPE EMG-1, APPROXIMATE CALIBRATION CURVES (M-445720, Sub 0).

FIGURE 24

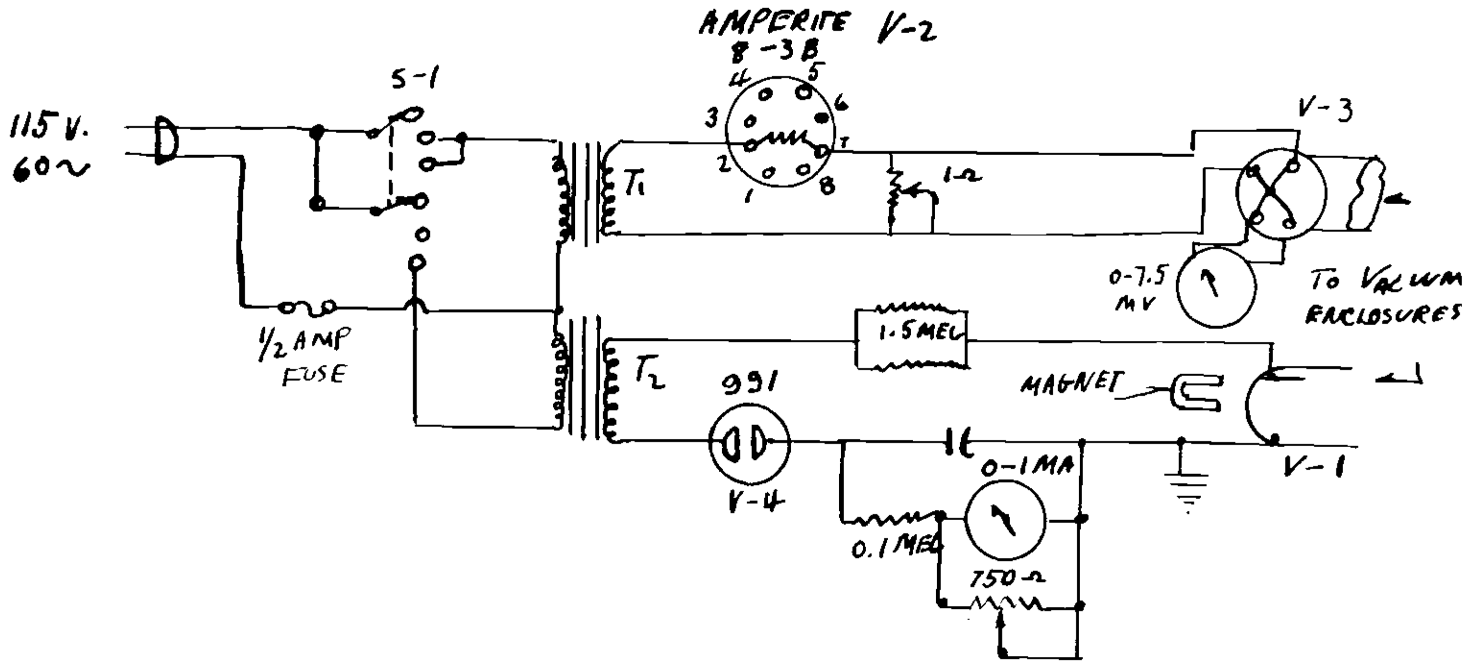
In the Vacuum Gauge Unit voltage was supplied to the discharge tube by the secondary of transformer T_2 (see Figure 25), and the current was limited by a 1.5 megohm resistor to a maximum of 3 milliamperes. A capacitor by-passes alternating current around the dc milliammeter which measures the discharge current. As the pressure decreases to 200 microns, the discharge occurs, and alternating current flows in the circuit lighting the 991 neon tube V-4. As the pressure is reduced further, the discharge tube V-1 begins to rectify and continues to do so to the limit of pressure reading. When V-1 begins to rectify, V-4 glows only on one side. This glow tube acts as a rough pressure gauge. The control circuit diagram is given in Figure 25. For a given reading of the dc milliammeter there are two possible pressures. By cross-checking the thermocouple gauge reading, it is simple to pick the correct value for the pressure.

Another method of measuring the pressure was the vacuum tube ionization gauge. The tube used throughout this experiment was the EIMAC 35-T IG (Eitel-McCullough, Inc., San Bruno, California). The manufacturer supplied the following information.

Plate Voltage	E_p	- 20 volts
Grid Voltage	E_g	150 volts
Grid Current	I_g	5 milliamperes
Filament Voltage	3.5 to 4.5 or 7.5 volts if necessary	
Filament Current		4 to 6 amperes

Pressure $P = 6 \times 10^{-5}\ I_p$(mm of Hg.) if I_p is in microamperes.

The tube was a conventional triode; all elements except the plate terminated in a four-prong socket. The plate or collector was led out



CONTROL CIRCUIT FOR USE WITH
VACUUM GAUGE UNIT
TYPE EMG-1

see R. G. Picard, P. C. Smith, S. M. Zollers
REV. SCI. INST. 17, 125 (1946)

FIGURE 25

through the envelope. The filament was heated with alternating current so as to give a constant electron current I_g of 5 milliamperes. With this fixed supply of electrons accelerated by the grid at 150 volts potential, the rate of ionization was proportional to the molecular concentration. These positive ions were collected at the negative plate. The resulting plate current was proportional to the molecular concentration over wide ranges of pressure. Guthrie and Wakerling[8] stated that this holds in linear fashion from 10^{-3} mm to 10^{-8} mm of mercury.

The diagram of the ionization gauge control circuit is given in Figure 26. A relay in series with the grid circuit was used to control and maintain the grid current at 5 milliamperes.

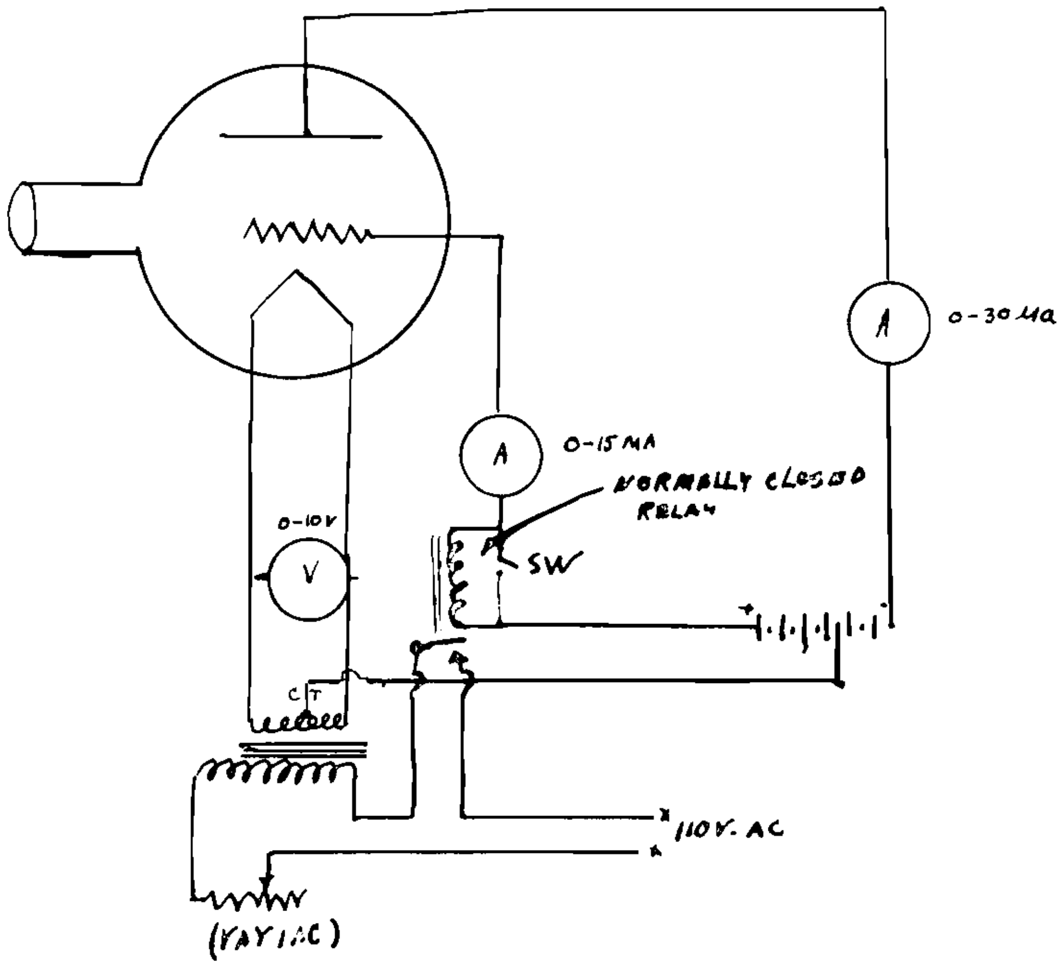
Since there were no calibration curves available for this tube, several tests of the tube chacteristics were made. These were made over a range of pressure from 10^{-3} to 6×10^{-6} mm of mercury and for several grid currents from 1 to 13 milliamperes. A typical calibration curve of log collector current versus log pressure is given in Figure 27. The pressure was measured with a Phillips gauge. A plot of plate current I_p versus grid current I_g is shown in Figure 28. From these curves it would be possible to use a larger grid current so that the pressure could be measured with a less sensitive meter.

Pumping speeds were measured in this experiment, for both the fore pump and the diffusion pump, with the constant volume method.

Define pumping speed S

$$S = -\frac{dv}{dt},$$

[8] Ibid., p. 118.



CONTROL CIRCUIT FOR EIMAC 35T
IONIZATION GAUGE

FIGURE 26

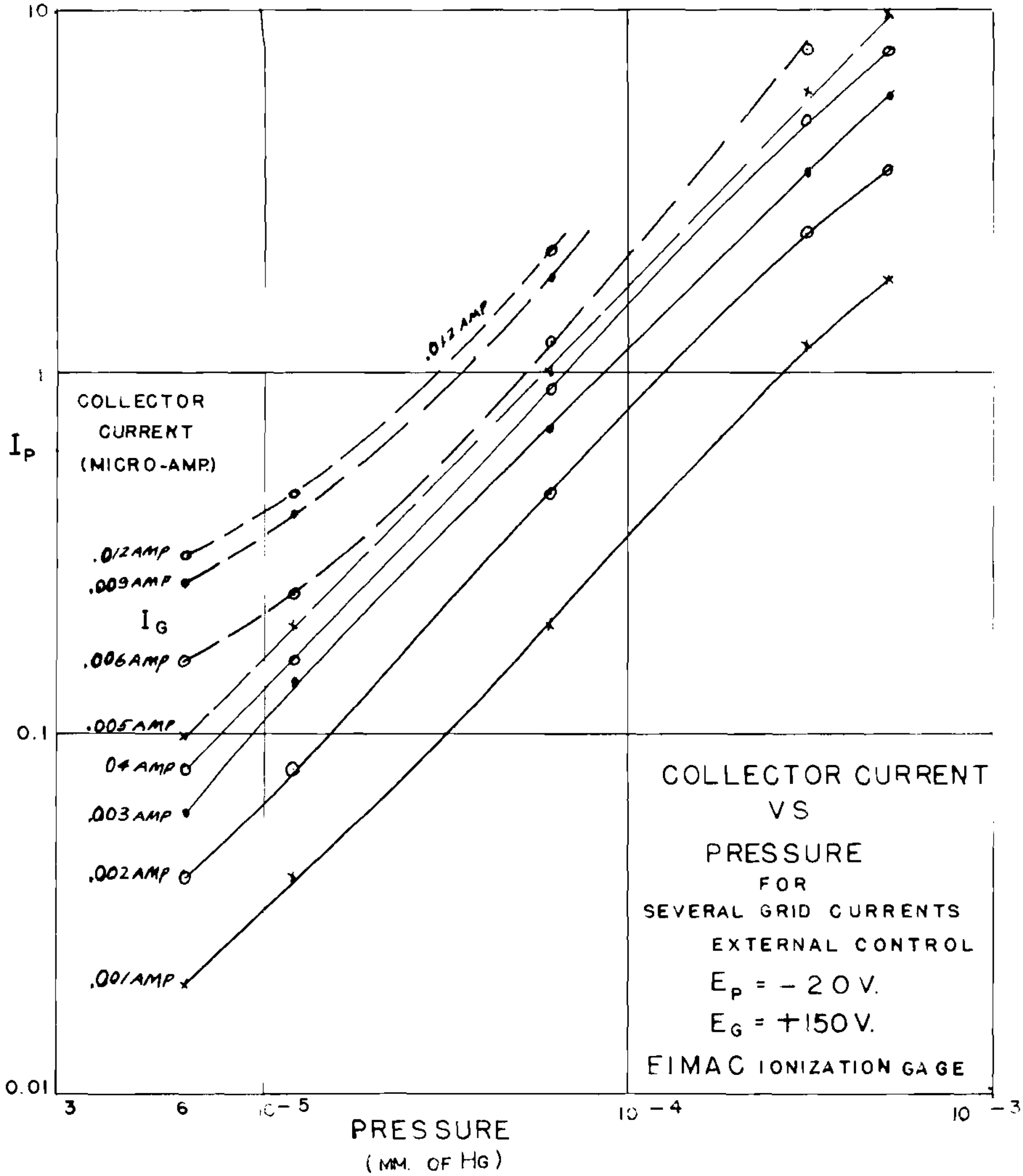

10
1
0.1
0.01
3
6
10 −5
10 −4
10 −3
PRESSURE
(MM. OF HG)
I_P
COLLECTOR CURRENT (MICRO-AMP.)
I_G
.012 AMP
.012 AMP
.009 AMP
.006 AMP
.005 AMP
.004 AMP
.003 AMP
.002 AMP
.001 AMP
COLLECTOR CURRENT VS PRESSURE FOR SEVERAL GRID CURRENTS
EXTERNAL CONTROL
$E_P = -20$ V.
$E_G = +150$ V.
EIMAC IONIZATION GAGE

FIGURE 27

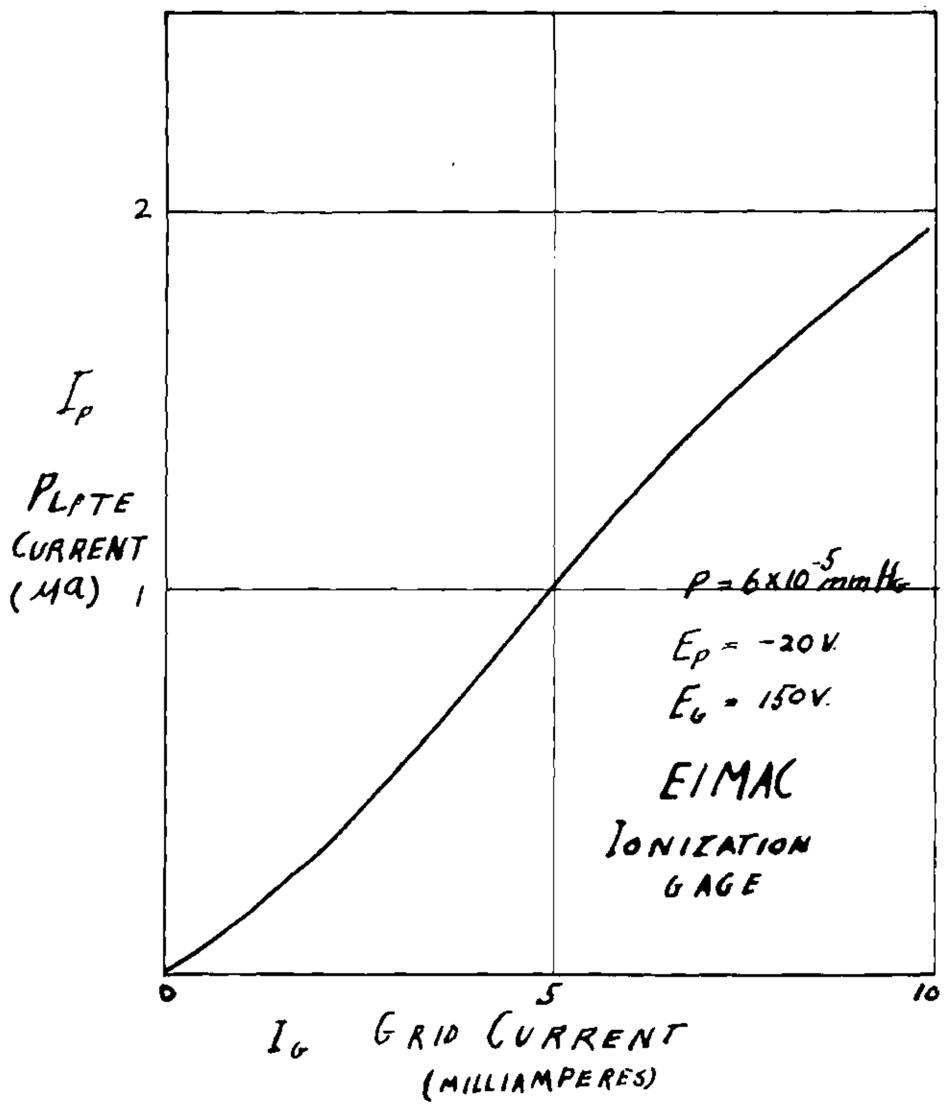

2
1
0
5
10
I_p
PLATE
CURRENT
(μa)
$p = 6 \times 10^{-5}$ mm Hg
$E_p = -20$ V.
$E_G = 150$ V.
EIMAC
IONIZATION
GAGE
I_G GRID CURRENT
(MILLIAMPERES)

FIGURE 28

where v is the volume. Boyle's law may be written

$$Pv = (P - dP)(v + dv) \ ,$$

and

$$\frac{dv}{dt} = -\frac{v}{P}\frac{dP}{dt} \ . \quad \text{(temperature constant)}$$

Therefore the pumping speed may be defined in terms of a fixed volume:

$$S = -\frac{v}{P}\frac{dP}{dt} \ .$$

Integration of the above equation from P_1 to P_2 and from t_1 to t_2, gives

$$S = \frac{v}{t_2 - t_1} \operatorname{Log}_e \frac{P_1}{P_2} \ .$$

In practice a definite limiting pressure P_o set by the limitations of the pump and the fluid is realized. Langmuir[9] defined the pumping speed as follows:

$$S = -\frac{v}{P - P_o}\frac{dP}{dt} \ .$$

If P_1 and P_2 are the pressures obtained in the enclosure at t_1 and t_2, then S may be taken as constant over the pressure range. Therefore

$$S = \frac{v}{t_2 - t_1} \operatorname{Log}_e \frac{P_1 - P_o}{P_2 - P_o} \ .$$

The kinetic theory of gases predicts that, at a pressure of 10^{-3} mm of mercury, the mean free path of the molecule is of the order of

[9] I. Langmuir, "The Condensation Pump: An Improved Form of High Vacuum Pump," General Electric Review, 19:1060, (1916).

magnitude of the dimensions of the diameters of tubing and various apertures of the normal vacuum system. If the mean free path is greater than the tubing diameters, the gas flow is molecular in character, rather than hydrodynamic, and is no longer a function of the pressure. Under these conditions reference is often made to the "speed" or conductance of tubing just as reference is often made to the speed of a pump.[10]

For example, in a straight piece of tubing the speed is sometimes given as follows:

$$S \propto \frac{D^3}{L},$$

and for an aperture

$$S \propto D^3,$$

where D is the diameter, and L is the length.

If S' be the measured speed of exhaust of the system and S_1 and S_2 be the conductances of various parts of the system, and S_p be the actual rated speed of the pump alone, the following relation is applicable.

$$\frac{1}{S'} = \frac{1}{S_1} + \frac{1}{S_2} + \frac{1}{S_p}.$$

From this it is seen that the effective speed of exhaust of a system is dependent on many things besides the rating of the pump itself.

Many empirical formulae have been developed for computing the conductance of various tubing, and apertures for various gases. Most

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[10] C. H. Bachman, Techniques in Experimental Electronics, (New York: John Wiley and Sons, Inc., 1948), pp. 91-96.

of these can be found in Dushman.[11]

In taking the measurements on this system, the pressure was read at two different times, keeping the pressure changes small. The volume of the system was estimated, and no attempt was made to calculate the conductance of the tubing and apertures. Considering the performance data taken and the rating of the pump, it was assumed that the conductance of the system was of the order of 1 liter per second. In this method a principal source of error was leakage into the system. This resulted in lower measured pump speeds. The speeds of exhaust measured by this method are given in Figure 7 for the diffusion pump and in Figure 3 for the fore pump.

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[11]S. Dushman, Scientific Foundations of Vacuum Technique, (New York: John Wiley and Sons, Inc., 1949), pp. 84-125.

LEAK TESTING

In any vacuum system leaks will occur and should be eliminated or reduced. There are innumerable ways of testing for leaks, some of which are as follows:

1. Spark coil passed over outside of vacuum system.
2. Discharge tube in system.
3. Rate of rise measurements.
4. Sealing substance on outside-change of pressure.

The use of a spark coil was limited to that one portion of the system that contained glass. As the spark coil passes over a leak in the glass, a bright spot on the glass indicates the hole.

The use of a discharge tube in the system entails watching the changing color of the discharge as some liquid or vapor is passed over the outside of the system. The glow discharge is useful only for pressures between a few millimeters and 10^{-2} mm of mercury. It is during this pressure range that the discharge is visible. As there is always some water vapor in the system, the color of the discharge is usually purple red. By passing carbon dioxide gas over the system part by part, joint by joint, a change in the color of the discharge to bluish-green indicates a leak. Many other liquids and gases can be used, but most of these do not give such a marked color change.

By isolating various suspect portions of the system and making a rate of rise of pressure measurement with the system closed, and then comparing this measurement with that of the entire system, leaks may be detected. This is a very sensitive method of leak detection, but by nature it is very tedious.

In an operating system if the leak is suddenly plugged up, a noticeable change in pressure will result if the system was previously at a stable pressure. Such rapid changes can be detected with a Pirani gauge or thermocouple gauge for a rough vacuum, or with an ionization gauge in the fine vacuum range. Temporary sealing substances used were wax, vacuum grease, or even water.

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